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Industrial ecology applied to ELV management. Material and energy recovery from ASR

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Know how to solve every
problem that has been solved
R. P. Feyman

Preface

This thesis is the result of a PhD study conducted at the Department of Industrial Chemistry and Materials of the University of Bologna, from January 2008 to December 2011.

The research project was funded by Gruppo Fiori and supervised by Professor Luciano Morselli. It involved a bibliographical research, laboratory activities, ecodesign and LCA software modeling, international congresses active participation, papers publication, practical work at the shredding plant and the participation to a PhD students exchange program.

Six papers were published during this three years on international journals with impact factor, and they are reported in this thesis as appendixes. They are referred to in the main text by their roman numerals and they form an integral part of the doctorate:

I. Santini, A., Herrmann, C., Passarini, F., Vassura, I., Luger, T., Morselli, L., Assessment of Ecodesign potential in reaching new recycling targets for ELVs, Resources, Conservation and Recycling, Volume 54, Issue 12, October 2010, Pages 1128-1134.

II. Morselli, L., Santini, A., Passarini, F., Vassura, I., Automotive shredder residue (ASR) characterization for a valuable management, Waste Management, 2010, 30, pp. 2228 – 2234.

III. Santini, A., Morselli, L., Passarini, F., Vassura, I., Di Carlo, S., Bonino F., End-of-Life Vehicles management: Italian material and energy recovery efficiency, Waste Management, 2011, 31, pp. 489 – 494.

IV. Ciacci, L., Morselli, L., Santini, A., Passarini, F., Vassura, I., A comparison among different automotive shredder residue treatment processes, Int J Life Cycle Assess 2010, vol. 15, no9, pp. 896-906.

V. Santini, A., Passarini, F., Vassura, I., Serrano, D., Dufour, J. and Morselli,L., Auto shredder residue recycling: mechanical separation and pyrolysis, Waste Management (2012) http://dx.doi.org/10.1016/j.wasman.2011.10.030

VI. Passarini, F., Ciacci, L., Santini, A., Vassura, I., Morselli, L., Auto shredder residue LCA: implications of ASR composition evolution , Journal of Cleaner Production, Volume 23, Issue 1, March 2012, Pages 28-36.

In addition, the following publications on broad diffusion sector magazines have been produced during the Ph.D. course:

I. Santini, A., ASR recycling via hydro-mechanical separation and pyrolysis, Recycling International, In the lab section, February 2012.

II. Morselli, L., Paludi, A., Santini, A., Car fluff. Dar valore al rifiuto, Plastix, October 2008.

III. Morselli, L., Passarini, F., Santini, A., L'ecodesign industriale per un recupero efficiente, Ecoscienza – ARPA (Environmental Regional Protection Agency) Emilia Romagna – 2011.

Bologna - January 2012

Summary

The present PhD thesis is part of a five-years teamwork between the University of Bologna – Department of Industrial Chemistry – and Gruppo Fiori, the largest Italian shredding company, and it was conceived to develop innovative car fluff management solutions. This work is focused on the industrial plant design and application of new technologies in the automotive recycling field.

The end of life vehicles (ELVs) recycling chain has to comply with European regulations, setting recycling and energy recovery targets for 2015 with Directive 2000/53/CE. More specifically, materials embodied in cars will have to be recycled for at least 85% by weight. The remaining non-recyclable fraction has to be thermally recovered for another 10% by mass, rising recoverability rate to 95%. Practically, from 1st January 2015, only 5% of a vehicle will be allowed to end up in landfills. Midterm targets were set in 2006, equal to 80% recycling rate and 90% recovery rate. The European situation at that time was rather fragmented, both for recycling performances and national law allowances, especially concerning pretreatment, de-pollution operations and thermal recovery authorizations. This study has been carried out to find solutions to the biggest challenge in car shredding industry: the auto shredder residue (ASR) recycling.

At the beginning, it was necessary to understand the Italian state of the art of car recycling in order to decide the technological and management solutions that were necessary to reach the targets. At a first glance, these targets would really modify the car recycling industry. Generally, only steel and other non ferrous metals were recycled, amounting at roughly 70% by mass. In addition, some de-pollution operations, like battery and fluids removal, were carried out rising the recycling quota to a scarce 75%. Car component dismantling is extremely expensive in terms of labour cost and this is the main reason why end of life cars get shredded and not completely disassembled. Moreover, cars are not yet specifically designed to be disassembled (see appendix, I) and thus all the nonmetallic materials that are not removed as reusable components, once shredded, become car fluff. In numbers, the remaining 25% of a ELV is landfilled in most European countries, and incinerated for a small share.

Car fluff is a very heterogeneous waste. It is generated after metal separation step at shredding plants and its material composition still reflects all that can be found in a End of Life Vehicle like residual metals, glass, plastics, foam rubber but also dirt, rust, soil and other pollutants. Moreover, ASR particulate size is extremely irregular: fines (> 20mm) may account for up to 50% but they can be found together with pieces of metal or foam rubber more than 250mm long per side in the same sample. Moreover, depending on de-pollution step efficiency, pollutants such as hydrocarbons, PCBs and mineral oils can be found in this waste. More details on car fluff characterization can be found in Appendix II. Despite the high added value content of metals and cables, the very particular car fluff composition made it historically difficult to recycle.

At first, it was necessary to study the exact composition of this waste, and also perform some chemical-physical analysis, to comprehend the potential treatments it could undergo. The aim was ASR recycling and then environmentally safe disposal of residues, according to EU waste framework directive. But the main scientific issue in car shredding was, and still is, that shredder plants do not process only ELV but also other waste such as industrial demolitions, white goods (i.e., washing machines) and separate collection. In addition, car fluff composition reflects the ELV mix at the hammer mill input. Thus, it was necessary to obtain a standard sample, representing both the average de-registered vehicles mix and the average de-pollution and dismantling operations depth. For this reason, it has been carried out a national recycling trial (thoroughly reported in appendix, III) arranged by FIAT, Italian Environmental Protection Agency (ISPRA), Ministry of Environment (MATTM), together with ELVs supply chain associations. The trial was coordinated

by ISPRA (Italian Environmental Protection Agency) and the University of Bologna (Department of Industrial Chemistry). This campaign revealed that if glass, bumpers, fuel tanks and tires are removed during dismantling, it is possible to achieve about 80% recycling rate after shredding. This was an important result and a basis for further investigation and legislation. In fact, a framework agreement was signed by all the participants who agreed to perform all the pre-shredding operations carried on during the trial. Now, in Italy, it is mandatory to remove bumpers, tires, windscreen and fluids from ELVs. Moreover, samples of car fluff were collected and characterized.

The target now was clear: to recycle at least 25% car fluff materials to meet the EC targets and prepare the remaining fraction to be thermally recovered. Bearing these main objectives in mind we proceeded with an LCA (Life Cycle Assessment) screening, comparing the existing ASR disposal technologies (appendix, IV). LCA is a holistic approach which defines industrial systems material and energy flows from cradle to grave. Functional unit of this study was 1 ton of ASR. The assessment revealed that landfilling, though is the most applied option in Europe, is the less environmentally sustainable. Removing residual metals from fluff boosts environmental performances since the impact of the avoided production of aluminum, steel and copper is very important. Finally, incineration following metals separation and recycling is another pathway to enhance sustainability. Two additional scenarios were created, representing innovative plastic sorting technologies and gasification followed by *syngas* reforming. These two scenarios indicated that polymers play a very important role in ASR recycling since they represent almost 40% of the total mass and the largest share of the gross calorific value (GCV). Particularly, thermo-chemical conversion of polymers allows to obtain at the same time electric energy and materials (char, cracking oils and gases) that could be further recovered or refined.

According to the LCA screening results, some ASR laboratory scale pretreatments and pyrolysis tests were performed during a PhD student exchange program at the Rey Juan Carlos University, Madrid, Spain (detailed results are reported in appendix, V). Car fluff was sieved in order to remove the fine, inert fraction. Then, both coarse and fine fractions were floated to separate polymeric fraction. Moreover, polyolefin and foam rubber were sorted from the plastic mix for dedicated conversion tests. Results revealed that pretreatment is fundamental for a correct and efficient thermal conversion. Up to 60% conversion, which is the sum of produced oil and gas, was achieved on floated samples, while literature reports average raw car fluff conversion to be around 20%. In addition, foam rubber revealed to be not suitable material for recycling via pyrolysis but polyolefin reached 90% conversion, triggering important refining opportunities and ecodesign considerations.

During the third and last year of PhD course, the activity at the shredding company was intensified and industrial application of laboratory study and results were evaluated and installed. At first, non ferrous metals recovery from light fluff was experimented. Innovative sieving technologies have been applied to reduce the total ASR flow and to concentrate aluminum in fine and mid size fraction (30-70mm). A pilot plant was installed and results are encouraging: 50kg per hour of aluminum are currently recovered in the pilot plant at Italmetalli. After aluminum, other targets were stainless steel and copper cables, which are the most critical material for energy recovery. For the recovery of these materials a partnership with a firm dealing with magnetic lift and sorting machinery development and production, was established, allowing us to study, test and visit innovative machinery and complete ASR recycling lines and plants. During this period tests on pilot sorting lines have been carried out. Innovative equipments, such as dynamic ferrous material separator, high frequency eddy current separators and inductive proximity sensors air separators were studied and tested with a dedicated campaign. This experience allowed the design of a new heavy fluff

treatment line. Once the metals are completely removed, the residual heavy fluff <30mm can be considered a good feeding material for energy recovery plants.

Furthermore, during the same year, a thermodynamic cracking plant, property of Cracking Energy Machines Limited, has been studied. This technology falls in the plastic to fuel category and its aim is to convert end of life tires rubber into cracking oil and gas. Subsequently these products can be oxidized in power generators. In addition, the produced char could be used again as carbon black in the tire production industry. A master trial have been performed, mass and energy balances have been calculated and products have been characterized. Results are reported more in detail along the main text of this thesis. This technology is extremely innovative and it could have important applications in car fluff energy recovery as well.

According to the industrial ecology framework, relations between expected new car composition and car fluff evolution have been assessed (see appendix, VI). There is a 15 year delay between cars production and ELVs treatment. Thus, current car fluff composition reflects this 15 years time lag. The aim of this work is to understand whether the expected shifting from metals to plastics in new vehicles has effects on recycling rate and environmental performances in the previously created scenarios (IV). Another evaluated scenario is the reduction of polymeric families according to the rules of design for recycling. Results indicate that ecodesign can really reduce the environmental impact of ASR treatments and, along with plastic sorting, enhance ELVs recycling rate.

Finally, during this PhD, many international congresses have been attended and presentations given. In this way, some international relationships and interesting discussions with authors coming from different Countries arose, thus contributing to understand the world state of the art in this field. This knowledge broadened the array of possible treatments that could be suitable for car fluff also in Italy, and gave interesting points of view for future investigation.

Riassunto

La presente Tesi di Dottorato costituisce parte integrante di un lavoro condotto nell'arco di cinque anni mediante una Convenzione tra l'Università di Bologna – Dipartimento di Chimica Industriale – ed il Gruppo Fiori, azienda che opera nel settore della la raccolta e il riciclo di materiali ferrosi e non ferrosi e, più specificatamente nel recupero degli ELV (*end-of-life Veichles)*, Veicoli a fine Vita. Obiettivo della collaborazione è stato quello di ricercare e sviluppare soluzioni innovative per la gestione del residuo di frantumazione auto non ancora recuperabile*,* il car fluff (o *ASR, Auto Shredder Residue)* da cui discende il programma della Tesi di Dottorato la cui borsa di frequenza è stata sponsorizzata dalla stessa azienda.

Il processo di recupero di materiali ed energia dai veicoli a fine vita fa riferimento alla Direttiva 2000/53/CE ed ai target previsti al 2015. Nello specifico, è richiesto un riciclo di materiali per almeno l'85% del peso di un ELV e la frazione rimanente non riciclabile va recuperata energeticamente per un altro 10% in massa, raggiungendo così un recupero complessivo del 95%. Concretamente, dal gennaio 2015, solo il 5% di ogni veicolo a fine vita potrà essere smaltito in discarica. La Direttiva stabilisce anche obiettivi a medio termine, come quello del 2006, che richiedeva un 80% di riciclo e un 90% di recupero. In questo contesto la realtà europea risultava essere piuttosto disomogenea, diversificata tra i vari paesi membri soprattutto riguardo le concessioni legislative particolarmente incentrate sul pretrattamento, le operazioni di decontaminazione e le autorizzazioni per il recupero termico. Questo studio è stato incentrato quasi esclusivamente su una frazione proveniente dalla frantumazione degli ELVs, il recupero dell' ASR.

Nella prima fase si è proceduto una ricognizione dello stato dell'arte in Italia ed in Europa al fine di impostare un approccio metodologico sulle soluzioni tecnologiche e gestionali necessarie a raggiungere gli obiettivi prefissati, atti a modificare la filiera industriale in modo profondo ed innovativo. In generale, il punto di partenza era legato al recupero preminentemente dell'acciaio e altri metalli non ferrosi, per un 70% totale in massa. Altri aspetti riguardavano le altre fasi di trattamento quali la bonifica preliminare al trattamento con la rimozione delle batterie e dei fluidi inquinanti, ed al disassemblaggio di parti facilmente recuperabili e riciclabili quali vetro, paraurti, pneumatici ed altro portando la percentuale ad 75%. Sovente la demolizione di un'automobile è un processo estremamente costoso qualora non vengono effettuate procedure di disassemblaggio e bonifica al fine di ottenere flussi di materiali facilmente recuperabili, motivo per cui i veicoli a fine vita vengono frantumati direttamente. Va aggiunto che le auto, considerando il loro Ciclo di Vita, non vengono ancora progettate con gli accorgimenti del facile disassemblaggio (si veda *Appendix I*), quindi i materiali non metallici che non vengono preventivamente rimossi come componenti riutilizzabili, una volta frantumati diventano car fluff. In cifre, il 25% risulta essere il residuo da un ELV non risulta valorizzabile e destinato alla discarica nella maggior parte dei casi e per una piccola quota inviato al recupero energetico con trattamenti termici..

Il car fluff è un rifiuto dalla matrice molto complessa la cui composizione, in qualità, riflette spesso i componenti di un veicolo a fine vita come metalli, vetro, plastiche, gommapiuma, ma anche detriti, ruggine ed inquinanti. La pezzatura dell'ASR è estremamente irregolare: la parte fine (> 20mm) può rappresentare oltre il 50% ma nello stesso campione si trovano anche pezzi di metallo o di gomma lunghi più di 250mm. Inoltre, a seconda dell'efficienza della fase di decontaminazione, si riscontrano elementi quali idrocarburi, policlorobifenili e oli minerali (*Appendix II*) Nonostante il contenuto ad alto valore aggiunto del recuperabile, costituito da metalli e cablaggi elettrici (rame), la composizione così particolare del car fluff lo ha reso un materiale storicamente difficile da trattare.

In primo luogo è stato necessario caratterizzare la matrice dal punto di vista merceologico e chimico-fisico allo scopo di impostare sistemi di separazione per flussi omogenei, verificare la presenza di inquinanti pericolosi, da qui considerare l'intera filiera di procedure di bonifica, separazione e stoccaggio provvisorio delle varie frazioni e considerare interamente le Linee Guida nel quadro della direttiva UE sui rifiuti 98/2008/EC. Parallelamente, il problema scientifico riguardante la demolizione delle auto era, e lo è tuttora, che gli impianti di demolizione non si occupano solo degli ELVs ma trattano anche altre tipologie di rifiuti da demolizioni industriali, soprattutto RAEE o da raccolta differenziata da aziende del settore. Inoltre, la composizione del car fluff riflette l'insieme dei materiali dei veicoli a fine vita che vengono convogliati dentro il mulino, veicoli deregistrati a diverso grado di bonifica e/o disassemblaggio. E' stato necessario a questo punto ottenere un campione statistico che rappresentasse la realtà nazionale del mix proveniente dai veicoli dalla raccolta dedicata (dai rottamatori) sul quale poter operare tutta una serie di indagini sul mix stesso, ma anche attivare una progettualità allo scopo di rapportarsi ad una indagine ad ampio raggio nazionale. A questo scopo è stato realizzato un trial a livello nazionale sul riciclo (riportato in modo approfondito in *Appendix III*) organizzato da FIAT, dall'Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), dal Ministero dell'Ambiente (MATTM) e dalle associazioni industriali di filiera che hanno sottoscritto un Accordo di Programma Quadro con il Min. dell'Ambiente (AIRA, ANFIA, UNRAE, FISE, UNIRE , etc.). Referenti scientifici sono stati ISPRA e l'Università di Bologna (Dipartimento di Chimica Industriale). Secondo questo studio iniziale, cristalli, parafanghi, serbatoi e pneumatici se rimossi e riciclati durante la rottamazione permettono il raggiungimento dell'80% circa di riciclabilità degli ELVs, un risultato notevole che avvicinava il target italiano alla media europea, ma anche un incentivo per ulteriori ricerche e procedure.

In seguito ai risultati del trial, l'obiettivo era chiaro: recuperare in vario modo in materiali e attraverso recupero energetico in vario modo gran parte del 25% che rappresenta il car fluff per rispettare i target dell'UE. Per valutare come raggiungere l'obiettivo è stata realizzata un'analisi LCA che ha confrontato le tecnologie di smaltimento ASR esistenti (*Appendix IV*). L'LCA ha un approccio olistico che definisce i materiali dei sistemi industriali e i flussi energetici "*from cradle to grave*". L'unità funzionale di questo studio è stata 1 tonnellata di ASR. La valutazione ha rivelato che lo smaltimento in discarica, anche se è l'opzione maggiormente utilizzata in Europa, è quella meno sostenibile dal punto di vista ambientale. Il recupero di metalli residui dal car fluff migliora notevolmente l'impatto ambientale dal momento che può evitare la produzione di ulteriore alluminio, acciaio e rame. Infine, l'incenerimento a seguito della separazione dei metalli ed il loro riciclo sono altre strade percorribili per aumentare la sostenibilità del processo. Sono stati ipotizzati altri due scenari, ovvero uno sulle tecnologie più innovative per la selezione delle plastiche e quello sulla gassificazione seguita dal processo di reforming del syngas a metanolo. Questi due scenari hanno mostrato che i polimeri giocano un ruolo fondamentale nel riciclo del *car fluff*, dal momento che rappresentano circa il 40% della massa totale e la quota più grande del potere calorifico (PCI). Nello specifico, la conversione termochimica dei polimeri permette di ottenere contemporaneamente energia elettrica e materiali (residui carboniosi, oli derivati dal cracking e gas) che possono essere ulteriormente recuperati o raffinati.

A seguito dei risultati ottenuti dallo screening LCA, alcuni campioni di *car fluff* provenienti dal trial sono stati pretrattati e pirolizzati mediante un reattore da banco durante un exchange program presso la Universidad Rey Juan Carlos, Madrid, Spagna (risultati più dettagliati sono riportati in *Appendix V*). Il *car fluff* è stato setacciato per rimuovere i componenti fini e la frazione inerte. Successivamente, sia la frazione fine che quella grossolana sono state fatte flottare per separare la frazione polimerica. Sia le poliolefine che la gommapiuma sono stati selezionati dal mix di plastiche per condurre dei test specifici di conversione termochimica. I risultati hanno rivelato che il pretrattamento della matrice car fluff in un flusso più

compatibile al trattamento, è fondamentale per una conversione termica corretta ed efficiente. Dai campioni sottoposti a flottazione si è ottenuto il 60% di conversione, che rappresenta la somma di olio e gas mentre in letteratura si parla di un 20% medio di conversione del car fluff grezzo. La gommapiuma non si è rivelata adatta al recupero termico mediante pirolisi, ma le poliolefine hanno raggiunto il 90% di conversione, suggerendo grosse potenzialità di raffinazione e dando adito a considerazioni di ecodesign.

Al principio del terzo e ultimo anno di dottorato, l'attività presso il Gruppo Fiori si è intensificata: l'applicazione industriale degli studi di laboratorio ed i conseguenti risultati sono stati valutati in ottica industriale e applicati. In primo luogo è stato sperimentato il recupero dei metalli non ferrosi dal fluff leggero. Sono state adottate tecnologie innovative per vagliare e ridurre il flusso totale di ASR, concentrando l'alluminio nella frazione fine e media (30-70mm). È stato quindi installato un impianto pilota dedicato. I risultati sembrano incoraggianti: attualmente vengono recuperati circa 50kg all'ora di Alluminio. Altri materiali presi in esame sono stati l'acciaio inossidabile e i cavi di rame, che rappresentano i materiali più critici per il recupero energetico, ma importantissimi ai fini economici. Per il recupero di questi, è nata una collaborazione con un'azienda che si occupa dello sviluppo e produzione di macchinari per la separazione magnetica dando modo all'azienda di studiare, testare e valutare macchinari innovativi, o parte di essi, e completare le linee di lavorazione dell'ASR. Nel corso di questo periodo di prova sono state costruite delle nuove linee di selezione. Sono state inoltre studiate e testate attraverso un'analisi specifica alcune attrezzature innovative quali un separatore dinamico per il materiale ferroso (D-SRP), dei separatori a correnti parassite ad alta frequenza e dei separatori ad aria con sensori induttivi di prossimità. Tali esperienze hanno portato alla progettazione di una nuova linea di trattamento del fluff pesante. Una volta rimossi totalmente i metalli, il fluff pesante rimanente (<30mm) può essere considerato un buon materiale di alimentazione per gli impianti di recupero energia.

Nel corso dello stesso anno si è anche studiato un impianto di cracking termodinamico di proprietà di Cracking Energy Machines Limited. La sua tecnologia ricade nella categoria "*plastics to fuel*" e mira a convertire la gomma dei pneumatici a fine vita (PFU) in olio combustibile e gas. Questi prodotti possono essere successivamente ossidati in generatori elettrici. Inoltre, il carbone prodotto potrebbe essere usato nuovamente come *carbon black* nell'industria per la produzione di pneumatici, ma mancano ancora diversi aspetti di caratterizzazione. È stato fatto un master trial e i bilanci di massa ed energia sono stati calcolati e i prodotti caratterizzati. I risultati sono riportati in modo dettagliato nel corpo della tesi. Questa tecnologia è estremamente innovativa e potrebbe avere importanti risvolti anche nel recupero energetico dal *car fluff* pesante.

Nel quadro dell'ecologia industriale sono stati valutati i rapporti tra la composizione prevista delle nuove auto e l'evoluzione del car fluff (vedi *Appendix VI*). Il tempo che intercorre tra produzione di automobili e trattamento degli ELVs è di 15 anni: la composizione del car fluff attuale riflette la composizione dei veicoli di 15 anni fa. Fra gli obiettivi di questo lavoro c'è quello di comprendere se il cambiamento previsto nei nuovi veicoli (diminuzione dell'acciaio e incremento dei polimeri) possa avere effetti sul tasso di riciclabilità e sulle performance ambientali negli scenari citati in precedenza (*Appendix IV*). Un altro scenario allo studio è la riduzione delle famiglie di polimeri secondo le regole dell'*ecodesign*, in particolare della sua declinazione "progettazione per il riciclo". I risultati mostrano che l'*ecodesign* può effettivamente ridurre l'impatto ambientale dei trattamenti dell'ASR e, assieme alla selezione della plastica, migliorare il tasso di riciclabilità degli ELVs.

Infine, durante questo dottorato il candidato ha frequentato e esposto i propri risultati a numerosi congressi internazionali e nella pubblicazione di diversi lavori di buona diffusione. Ciò ha permesso al

Gruppo di lavoro di appartenenza ed al candidato stesso di instaurare relazioni internazionali interessanti e dare inizio a stimolanti discussioni con ricercatori e tecnici provenienti a livello internazionale, ciò ha contribuito ad una visione a livello globale della problematica di questo settore. Tali stimoli hanno ampliato la gamma delle possibilità di trattamento del *car fluff* e apportato nuovi spazi nell'ipotizzare ricerche future.

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BACKGROUND

Industrial ecology applied to ELVs industry

"Why would not our industrial system behave like an ecosystem, where the wastes of a species may be resource to another species? (Frosch & Gallopoulos, 1989)

Industrial ecology is a new production paradigm that aims at resources and energy savings for a cleaner industry. It is based on Sustainable Development principles to "*meet the needs of the present without compromising the ability of future generations to meet their own needs*" (UN, 1987).

There is no doubt that sustainable development is a topic in engineering and technology (Dewulf & Langenhove, 2005). Europe has the world's highest net imports of resources per person, and its open economy relies heavily on imported raw materials and energy. Secure access to resources has become an increasingly strategic economic issue. The goal is to improve resource efficiency: *industrial Ecology* is *industrial* because it focuses on products design and manufacturing processes and it is *ecological* because many biological ecosystems are especially effective at recycling resources and thus are set as good examples for efficient cycling of materials and energy in industry (Lifset and Graedel, 2001). This new approach to our planet is totally different from the one used since the Second Industrial Revolution to the late Nineties which considered resources unlimited, as unlimited was our planet waste disposal capacity ('type I' ecology in Figure 1)

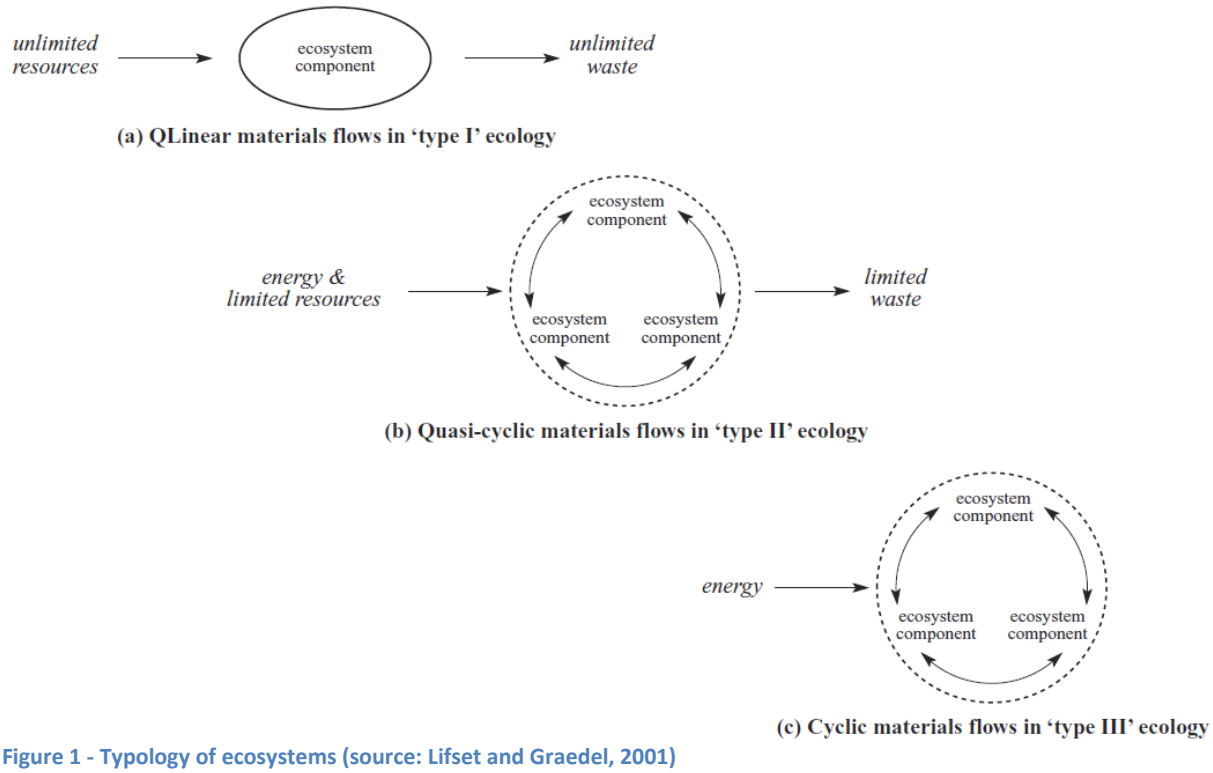


Figure 1 - Typology of ecosystems (source: Lifset and Graedel, 2001)

In an industrial ecosystem, the consumption of energy and materials is optimized, waste generation is minimized, and the effluents from one process serve as the raw material for another, as in 'type II' ecology in Figure 1 (Frosch & Gallopoulos, 1989).

A recent communication from the European Commission states: *"Europe has enjoyed many decades of growth in wealth and wellbeing, based on intensive use of resources. But today it faces the dual challenge of stimulating the growth needed to provide jobs and well-being to its citizens, and of ensuring that the quality of this growth leads to a sustainable future. To tackle these challenges and turn them into opportunities our economy will require a fundamental transformation within a generation – in energy, industry, agriculture, fisheries and transport systems, and in producer and consumer behaviour. Preparing that transformation in a timely, predictable and controlled manner will allow us to further develop our wealth and wellbeing, whilst reducing the levels and impact of our resource use"* (EC, 2011).

Industrial Ecology is made of five elements which are useful approaches, tools and practices through sustainability: design for environment, life cycle assessment, material flow analysis, industrial symbiosis and policy approaches suggested by industrial ecological principles (Chertow, 2008).

Design for environment (DfE) is an approach to design that considers the whole product life cycle and integrates in the design step environmental characteristic such as recyclability, extended durability, material requirements and energy consumption. DfE aim at creating products whose components are easy to dismantle and reusable, mono-material, non-blended, with few joining elements and free of toxic substances. In brief it is possible to define DfE as the sum of the interaction between legislation, market and sustainable development requirements. To act during the design stage is essential because the ability to influence the product properties, and this includes both environmental and technical performances, is greater in the planning and development phases, when the product is still an idea and the freedom of changing structure, material and joinings is at its maximum. During each following phase, aspects such as technical properties, economic properties and environmental properties of the product are taken more or less into account, and the final product usually comes out as a compromise between the different priorities. Moreover, after design the good has already been built and so forth it is not simple to improve its performances. Nevertheless, in use and End-of-Life (EoL) phases it is possible to gather enough information about the critical aspect of the product on recycling-relevant parameters to trigger a feedback information effect to the project team that, by gathering the missing information, now has the possibility to develop a new product with improved EoL performances. To develop these potentials, a feedback loop from the EoL stages to the product development is much needed, as designers do not generally have the experience in disassembly and recycling to determine the impacts of various design aspects on the product disassembly and recycling.

Life cycle assessment (LCA) is an analytical tool born to quantify environmental impacts over products life cycle. LCA con offer a quantitative comparison between alternative product or process design. It is a "cradle to grave" approach used to quantify and qualify carbon footprints, greenhouse gas inventories, toxics, and energy payback, among other impact categories. When conducting an LCA, it is necessary to consider energy and material flows involved in a process through the input and output stages with respect to an appropriate unit, so that all flows are considered on an equal footing. Such a unit is called the functional unit and can take a number of forms including mass, volume or a given number of a manufactured article. Data is collected for all life cycle processes on input (resources, components, semi products, chemicals, energy) and output (emissions to air, water and soil, waste, -semi- products, energy) summed over life cycle stages or over the entire life cycle. During life cycle impact analysis (LCIA) step resources consumed and emissions generated are calculated and quantified by means of environmental and toxicological impact categories, which are then to be weighted for importance. Finally, during the interpretation step a comparison between alternatives score is carried out and conclusions are drawn

Material flow analysis (MFA) is a method to map and quantify the flow of materials through a network of actors, be they in a single facility or group of facilities, a defined region, o along a product supply chain. By means of MFA it is possible to spot how resources flow, when and how long they are used and where can be mined.

Industrial symbiosis (IS) is based on the concept of exchange where one facility's waste (energy, water or materials) become another facility feedstock. Waste production is a continue leak of materials and Energy from the economic cycle and it entails both economic and social costs for collection, treatment and disposal. IS aims at waste prevention by upgrading it to a valuable resource.

Environmental policies are the law enforcement of sustainability principles. One among all: Extended Product Responsibility (ERP) imposes to the manufacturers the responsibility for the environmental impact and performances of their product during its later life cycle stages. The Organization for Economic Cooperation and Development defines it as "an environmental policy approach in which a producer's responsibility, physical and/or financial, for a product is extended to the post-consumer stage of a product's life cycle". ERP can be seen as the economic incentive for designing product with improved EoL performances.

Applying the *industrial ecology* principles into ELVs industry *means* the *shifting of industrial process from linear systems (type I)*, in which resource and capital investments move through the system to become waste, *to a closed loop system* (type II or III) where waste become inputs for new processes. Actually, in automotive industry capital, resources and energy are turned into cars, but since these products do not last forever, after a certain time lapse cars become waste, and embedded non-recyclable parts ends straight in landfill. At the shredding plant waste is anything is produced with a high entropy content.

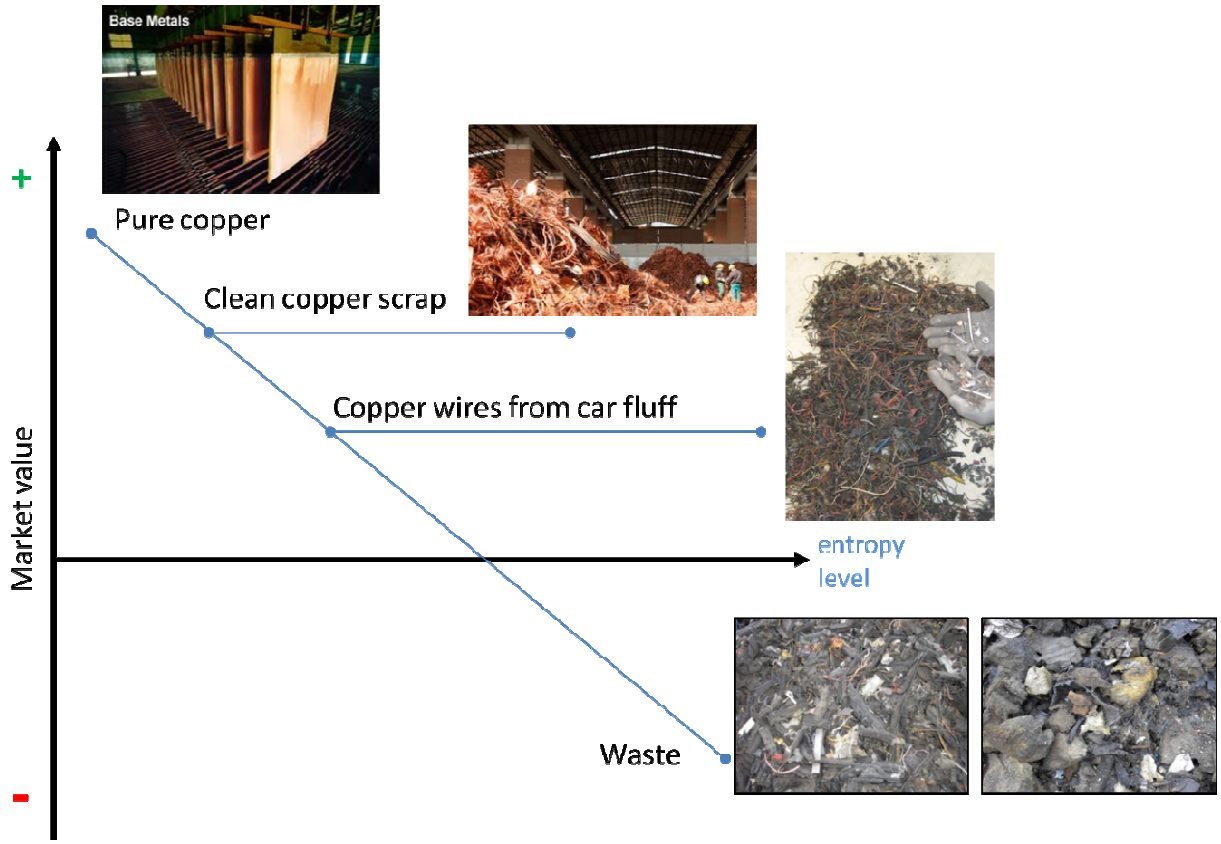


Figure 2 - Copper value against entropy level. Low Entropy level: market pays those who offer the material. High Entropy level: who offers the waste must pay for its disposal.

If a target material is mixed along with others, its value drops proportionally with the share of contaminants restrained. The price-drop basically represents the effort needed to put order into the mix, the Entropy of the system. In waste management, the Second Law of Thermodynamics brings that it is impossible to separate with 100% purity all the materials embedded in the waste and the more one gets closer to this hypothetic 100%, the more the input of energy, raw material or investments needed grows.

This is the reason why ELVs recycling is such a hard issue. ELVs are made of several materials, often blended, and after shredding they are mixed up, often tangled up together, thus the effort required to obtain products is considerable.

To apply industrial ecology in the automotive industry means to rise ELVs recycling rate, as required by Directive 53/2000/EC, which is the main aim of this PhD study. Stainless steel, copper, aluminum, brass and lead are continuously lost through ASR disposal as well as their embedded mining and refining energy.

ELVs European legislation

Being the continent in which cars have been designed, produced and developed for the first time (see Figure 3) it appears natural that the European Community is also the first institution which started to take into account the management of end-of-life vehicles (ELVs).

Figure 3 The candidate with an 1886 Benz, the first two stroke vehicle in the world and with a Ford T, fist mass production car (pictures taken during the 18th CIRP Congress at VW museum, Wolfsburg, Germany).

It was on October 1st 1908 that Henry Ford changed our lives with his most famous invention, the Model T car (Figure 3). The Model T was very simple to drive, and easy and cheap to repair. It was so cheap - at $825 in 1908, $20,100 today- that by the 1920s, the majority of American drivers had learned to drive on the Model T (Bak, 2003). Always searching for more efficiency and lower costs, in 1913 Ford introduced the moving assembly belts into his plants, which enabled an enormous increase in production. Sales surpassed the number of 250,000 units in 1914. By 1916, as the price dropped to $360[1] for the basic touring car, sales reached the number of 472,000 (Lewis, 1973).

Of course, nowadays cars are all over the world, especially in US and Europe, in which car ratio can reach up to 600 vehicles per 1000 citizens.

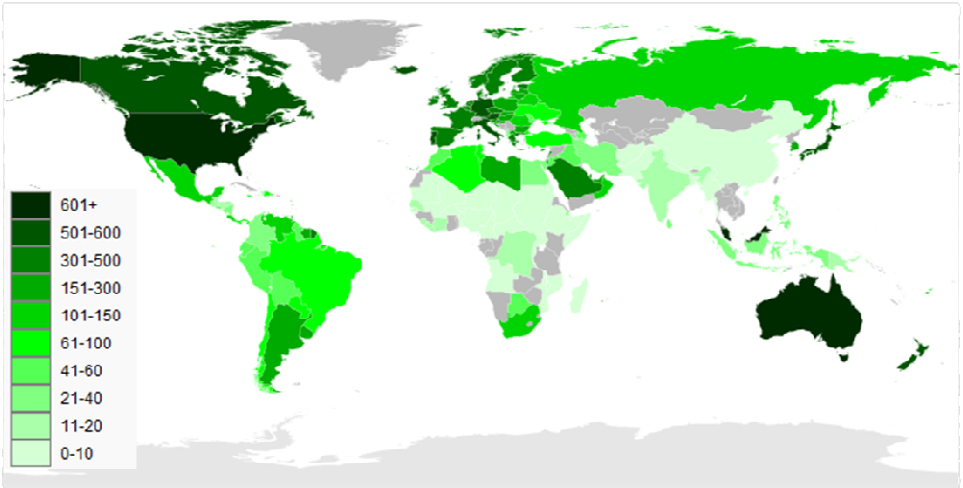


Figure 4 -World vehicles per capita in 2009 (source: http://commons.wikimedia.org/wiki/File:World_vehicles_per_capita.svg).

[1] Using the consumer price index, this price was equivalent to $7,020 in 2008 dollars.

Focusing on Europe, the current car fleets is close to 260M vehicles, and every year more than 10M vehicles are de-registered, as shown in Figure 5.

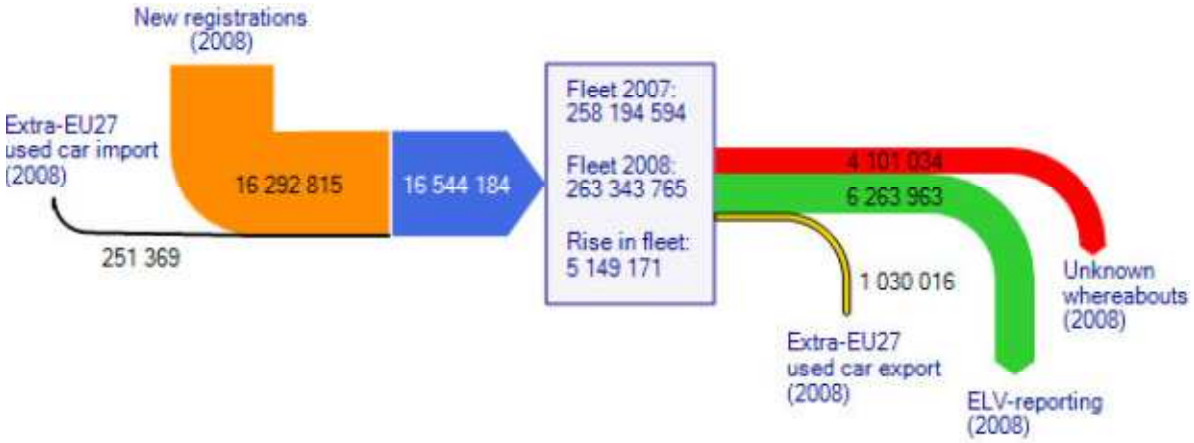


Figure 5 - Balance EU 27: fleet development in 2008 (source Hatzi-Hull, 2011)

Unfortunately, not all the ELVs enters their Member State (MS) recycling scheme. Almost 40% of them, in fact, are lost due to garaging of old vehicles or illegal activities such as abandon or export to other markets.

Concerning ELVs export, main routes are reported in Figure 6 and basically they pass from wealthier countries to lower economy countries (i.e. from Germany to Eastern States of Europe or from Italy to North Africa).

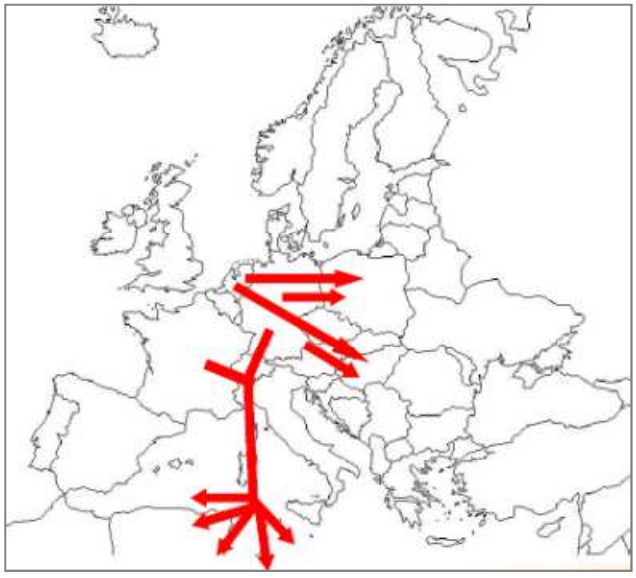


Figure 6 - Main export flows (source: Pensa, 2011)

In October 2011, exported ELVs in Italy reached 56% (Pensa, 2011). This massive flow is an actual loss of materials and profits for the ELVs treatment chain actors, and a real threat for shredders due to their high investment cost activity. Hulks shortage brings to both a rise in supply price and a conflict among shredding companies for the material itself to be processed, thus rising treatment cost per ton and reducing the pay-off. This condition, worsened by the financial crisis, which reduced the number of new vehicles sold (and thus ELVs produced), made imperative for shredders not to consider car fluff as a waste anymore, but a source of profitable materials.

On the other side, illegal disposal and ELVs abandon is environmentally dangerous because of the hazardous elements and materials contained in old cars (such as mercury in old switches, lead in batteries, chromium (VI) used once in electroplating process, PCBs containing old capacitors, hydrocarbons, mineral oils, etc.) and because these elements and molecules are even more dangerous when vehicles are illegally destroyed by fire (which is one of the most successful illegal disposal methods, together with sinking).

The European Community developed Directive 2000/53/EC, known also as the ELV Directive (EC, 2000) in order to minimize the environmental impact of ELVs, to reduce the final disposal, to improve the environmental performances of economic operators, to reduce the use of hazardous materials and to standardize treatment requirements (making sure that treatment facilities have a permit and have the necessary equipment to prevent pollution). This Directive, with an Industrial Ecology approach, involves:

1. extended producer responsibility (EPR) principles,
2. ELVs Reuse-Recycling and Recovery targets,
3. minimum treatment and de-pollution requirements and
4. mandatory MS yearly monitoring and reporting of results.

Extended producer responsibility forces manufacturers to merge end-of-life (EoL) relevant aspects directly into car design, with a life cycle approach. More specifically, ELV Directive limits the use of hazardous substances in new vehicles production, it stimulates producers to design more recyclable products (in order to reach targets), introduces standards for dismantling, recoverability and recyclability in type-approval Directive (2005/64/EC and ISO 22628:2002 calculation method) and promotes the use of recycled materials in new cars. According to 2010 ACEA Report (ACEA 2010), ELVs Directive Annex II is the driver for lifecycle emission reduction. In the last years a reduction of 99,6% in the use of lead, 96% in the use of cadmium, 99,9% in the use of chromium has been achieved (Hatzi-Hull, 2011). Additionally, mercury is phasing out. Organizational and financial responsibility is applied to all economic operators of the ELV treatment chain which have to set up collection systems and achieve reuse, recovery and recycling targets without return costs for end-user (free take back). MS have to guarantee adequate availability of collection facilities. Finally, responsibility is embedded in ELVs Directive also by introducing coding standards (IDIS, International Dismantling Information System - http://www.idis2.com- and IMDS, International Material Data System), promoting dismantling and components reuse by non-destructive pre-shedder operations, and by fixing the minimum treatments requirements (in Annex I)).

ELVs Recycling and Recovery targets are set in Article 7 of 2000/53/EC Directive. More specifically, materials embodied in cars will have to be recycled for at least 85% by weight by 2015. The remaining non-recyclable fraction has to be thermally recovered for another 10% by mass, rising recoverability rate to 95%. Practically, from 1st January 2015, only 5% of a vehicle will be allowed to end up in landfills. Midterm targets were set in 2006, equal to 80% recycling rate and 90% recovery rate. The European situation at that time was rather fragmented both for recycling performances and national law allowances, especially concerning pre-treatment, de-pollution operations and thermal recovery authorizations. It took almost two years to obtain and elaborate all the data from the MS, when in 2008, figures for 2006 situation (first compulsory reporting) showed the struggle to reach the targets and discrepancies in the methodologies that were used (see Figure 7).

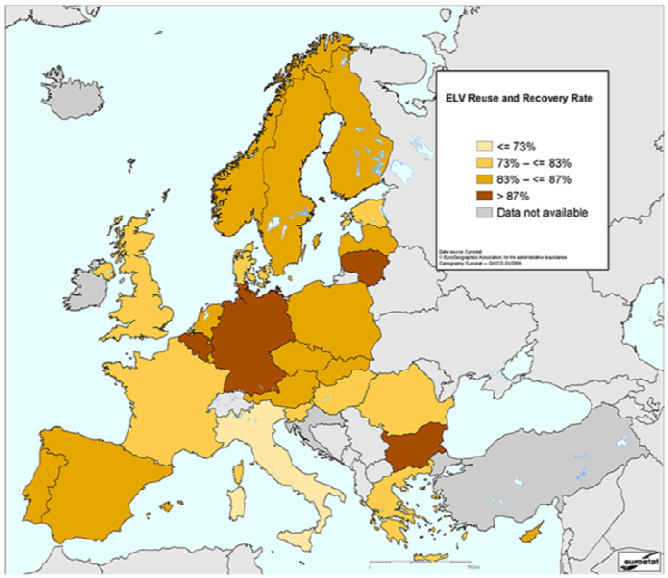


Figure 7 - 2006 ELV Reuse and Recovery Rate (source: Eurostat, 2008)

In order to solve this problem, working groups (Commission, Member States and industry) were created to agree on common methodology and, as a result, common guidelines for MS were issued. Italy performed its own national ELVs recycling campaign, further reported at "Italian Trial" paragraph and Appendix III. From 2008, the situation has been finally adjusted . Within two years all the MS, and their ELVs industry economic players, complied with the four points required by the ELVs Directive. Results were reported in 2010 by Eurostat website, with Figure 8, as follows.

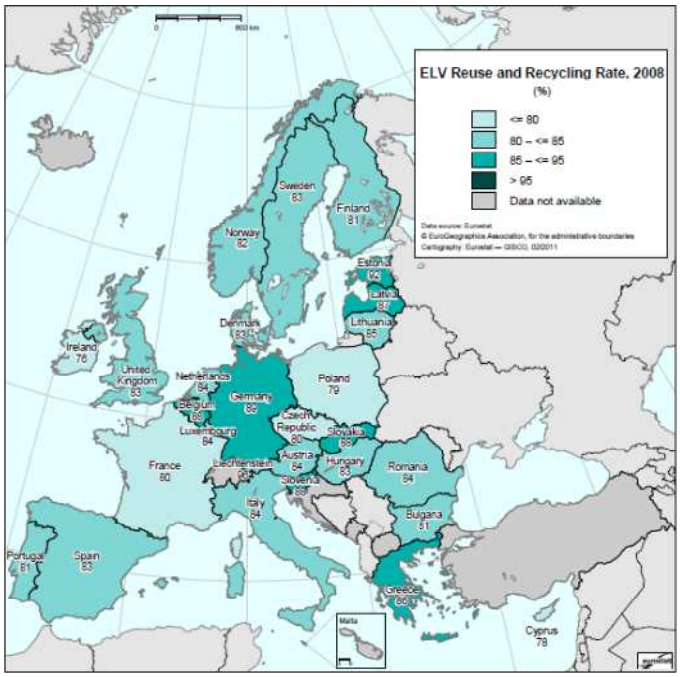


Figure 8 - 2008 ELV Reuse and Recycling Rate (source: Eurostat, 2011)

Directive 2000/53/EC laid down the basis for the current ELVs management, with a particular attention paid to environmental sustainability. ELVs Recycling and Recovery targets set by 2015 are very ambitious and will deeply modify ELVs treatment strategies. Auto shredder residue (ASR), a waste category currently amounting at a rough 20% of the initial ELV mass, shall be prevented or properly managed in a recycling-oriented perspective: residue metals and polymers will not be allowed to end up in landfills anymore and

ASR treatment shall consider energy recovery, by separating the non-combustible fraction to rise the efficiency of the whole process.

Great technological innovation is expected in the forthcoming years. Average weight per ELV is rising from the current 900kg to 1025kg estimated in 2020 (Hatzi-Hull, 2011). This means 17M tons of waste, typically vehicles currently on the road which have been registered in 2005, and more than 16M tons of material to recycle and recovery.

In the next chapter, the ELVs treatment chain is illustrated in detail, focusing on shredding industry and ASR production.

ELVs treatment in Italy

According to Directive 2000/53/EC, and its National enforcement D.lgs. 209/03, ELVs produced in Italy enter into a mandatory recycling scheme that involves depollution, dismantling, shredding , ASR recovery and disposal steps.

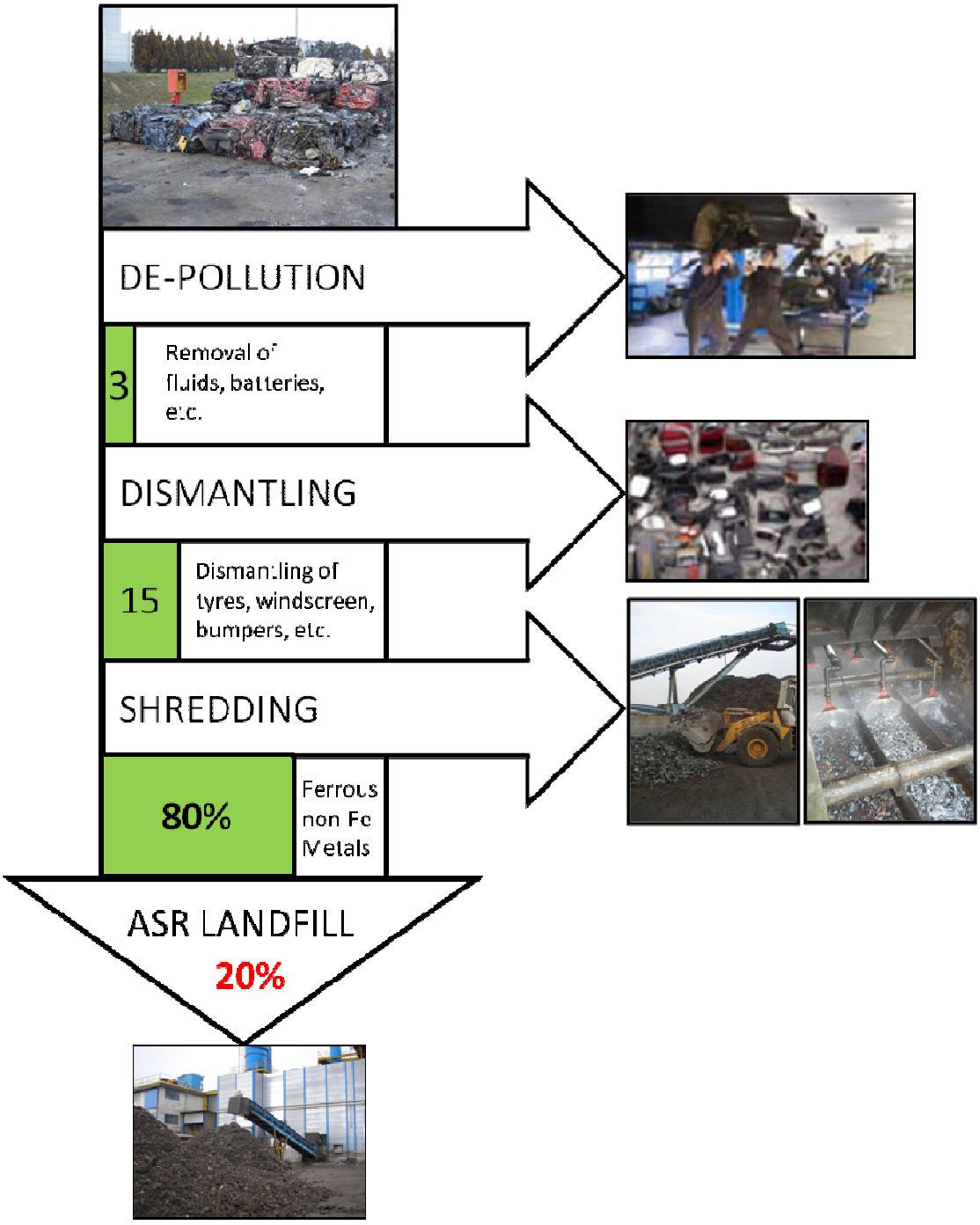


Figure 9 - Generic ELVs recycling scheme. The green boxes represent the average recycling rate achievable after each step, according to Santini et al., III. (picture souces: SGM; Di Carlo, 2008)

Most recent data on ELVs treatment and ASR production are reported as follows:

Reuse (t)	*Recycling (t)*	*Energy Recovery (t)*	*Total Recovery (t)*	*Disposal (t)*
190,561	937,037	39,058	976,096	212,370

In 2009 Italy, the 18% of ELVs mass is reused or recycled during depollution and dismantling steps. Little more than 3% of an ELV mass is recovered and total Recovery Rate is about 83% (Eurostat, 2011; ISPRA, 2011). Concerning energy recovery, Italy suffers from a structural weakness of the incineration plant framework , because they are not evenly distributed and the total capacity is not enough in many Regions, and because non-efficient infrastructures cause high transport costs.

Due to the financial crisis risen in summer 2008, the number of ELVs dismantlers is decreasing in the last years, as reported in the following table:

	2007		**2008**		**2009**	
	Plants	*ELVs treated (t/y)*	*Plants*	*ELVs treated (t/y)*	*Plants*	*ELVs treated (t/y)*
Northern	665	650,371	620	472,360	375	425,636
Central	283	269,608	242	204,380	221	242,412
Southern	459	445,572	459	389,220	453	464,086
ITALY	1,407	1,365,551	1,321	1,065,960	1,049	1,132,134

Currently, about a thousand of dismantles are working on the national territory (ISPRA, 2011).

The same trend is applied to shredder plants:

2009	*Plants*	*ELVs treated (t/y)*	*Other scraps*	*Fluff produced*
Northern	23	650,626	614,465	176,993
Central	5	184,334	71,635	54,180
Southern	10	173,883	202,907	55,459
ITALY	38	1,008,843	889,008	286,632

The spread between ELVs treated and ELVs shredded is mainly caused by export and/or stock at dismantlers' facilities. As reported in the next figure, export is growing in the latest years .This situation is critical for ELVs recycling industry because there is less material to process and industrial costs rise.

	Vehicles deregistered		Vehicles exported		Total	Variation (previous year)
2001	1.640.782	76,7%	215.038	10,1%	2.138.058	
2002	1.803.044	79,6%	224.875	9,9%	2.265.821	5,98%
2003	1.602.013	78,1%	268.372	13,1%	2.050.325	-9,51%
2004	1.406.489	74,3%	270.062	14,3%	1.892.234	-7,71%
2005	1.335.172	69,7%	389.294	20,3%	1.916.534	1,28%
2006*	1.599.634	73,7%	507.464	23,4%	2.171.578	13,31%
2007	1.850.819	70,2%	784.169	29,8%	2.634.988	21,34%
2008	1.426.190	65,2%	760.688	34,8%	2.186.878	-17,01%
2009	1.879.268	79,2%	493.576	20,8%	2.372.844	8,50%
2010	1.452.726	72,2%	560.723	27,8%	2.013.449	-15,15%
2011*	947.996	64,8%	515.532	35,2%	1.463.528	

Figure 10 - ELVs Italian deregistration and export (source: Pensa, 2011 – mod.)

Bearing this numbers in mind, the next two chapters explain more in detail operations and facilities involved in the Italian ELVs recycling scheme.

Depollution and component dismantling

Once a vehicle reaches its end-of-life and gets de-registered becoming an ELV, it has to be properly managed with the purpose of avoiding environmental pollution and to recover useful materials, especially metals. If an ELV is not depolluted properly by removing fluids, batteries and other hazardous components, a cross-contamination occurs during the shredding step and the landfilling or incinerating of residue fluff may bring to high environmental pollution, besides resources loss (mostly plastics and residue metals) and land use (Santini at al., I).

At first, fluids and other hazardous components, such as batteries, are mandatory removed. Then, according to the market rules, components may be dismantled and further reused and recycled, if it proves to be profitable. For the purpose of the ELV Recycling Rate calculation, all these component parts and materials are considered reusable or recyclable.

ELVs depollution is one of the most critical step in car recycling. At this step, the following vehicle component parts, materials or both shall be taken into account:

- all fluids;

- oil filters;

- liquefied petroleum gas (LPG) tanks, compressed natural gas (CNG) tanks;

- batteries;

- catalytic converters.

- tyres;

Fluids drainage is a very critical procedure because it aims at the removal of the most hazardous substances in the ELV. Residual fuels, lubricants and oils once passing at the shredding step cause hydrocarbons, heavy metals and mineral oils to pollute the shredder residue. This can direct to the classification of the shredder residue as hazardous waste, rising the management costs, and it can also burden air cleaning system of thermal recovery plants, when car fluff is following this route.

Oil filters are removed and drained. When the oil is almost gone, they are washed with a solvent, usually pentane.

Liquid petroleum gas (LPG) and compressed natural gas (CNG) tanks are very dangerous if they reach the shredding mill and they can explode when crushed by the hammers.

Batteries contain acids and lead, whose combination imply the heavy metal leaching. In Italy, a dedicated consortium (COBAT) take care of accumulators collection and recycling with its network.

Catalytic converters contain precious metals mainly platinum, palladium and rhodium (PGM). Even though the cordierite matrix in which they are sintered is very difficult to break, their value pushed some companies to develop cost-effective hydro-metallurgic and pyro-metallurgic processes to sort out noble metals. Beside, according to the Precautionary Principle inspiring European environmental policies, PGM effects on human health are still unknown so far EC decided that they shall be removed to avoid environmental contamination.

Tyres (ELT) have been used in cement works for many years (elimination + recovery of the calorific value). ELT consist of about 15% steel and for the remaining part of rubber. ELT can contain up to 1.5% sulphur and trace elements such as halogens which can cause harm to the environment and to human health, especially when ELT were burned illegally as often occurred in the past. A very innovative and promising technology for tyres conversion into diesel fuel have been studied by the candidate and it is reported more in detail in chapter "*Thermodynamic Cracking technology plant*".

After depollution, dismantling takes place. At this step, certain other of the vehicle's reusable or recyclable components parts may be taken into account. As a general requirement, a component part shall be considered as reusable, recyclable or both based on its dismantlability, assessed by:

- accessibility,

- fastening technology,

- proven dismantling technologies.

An additional requirement is that the reusability of a component part shall be subjected to consideration of safety and environmental hazard.

As a specific requirement, component parts shall be considered as recyclable, based on:

- material composition, and

- proven recycling technologies.

In order to be recyclable, a component part or material shall be linked to a proven recycling technology.

Accessibility, fastening technology and material composition, key parameters during dismantling, are design-related properties. An ecodesign study have been performed during the PhD and it is fully reported in Appendix I (Santini et al., 2010). In this paper, an ecodesign software, ProdTect have been developed and used to assess and reduce the dismantling time of a car seat. Main results are reported in the following text.

General end-of-Life (EoL) costs are described according to the following equation:
EoL Costs = Dismantling Costs + Disposal Costs - Reuse and Recycling Profits

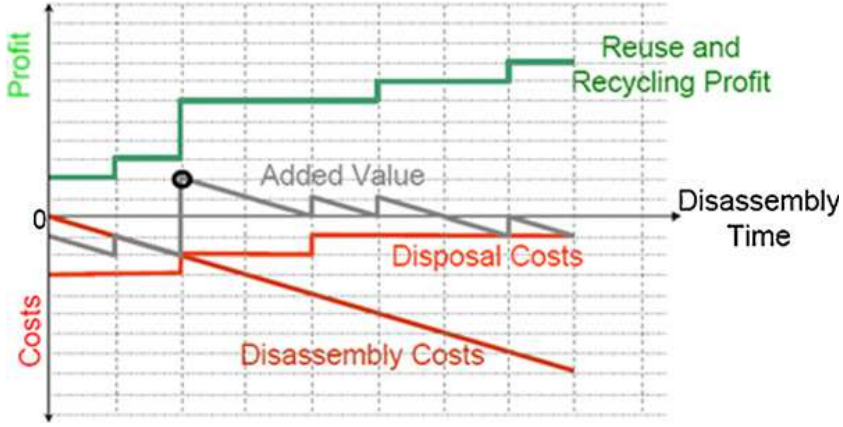


Figure 11- Generic EoL economics (source: Meißner et al., 1999, mod; Santini et al., I).

In Figure 11, the added value function represents at each step the solution of the EoL costs function.

The application of Design for Dismantling guidelines will lead to achieve earlier Reuse and Recycling Profits with less dismantling effort, compressing the Reuse and Recycling Profit function on the origin. At the same time, Profits are achieved in a shorter time, with time savings leading to less dismantling costs.

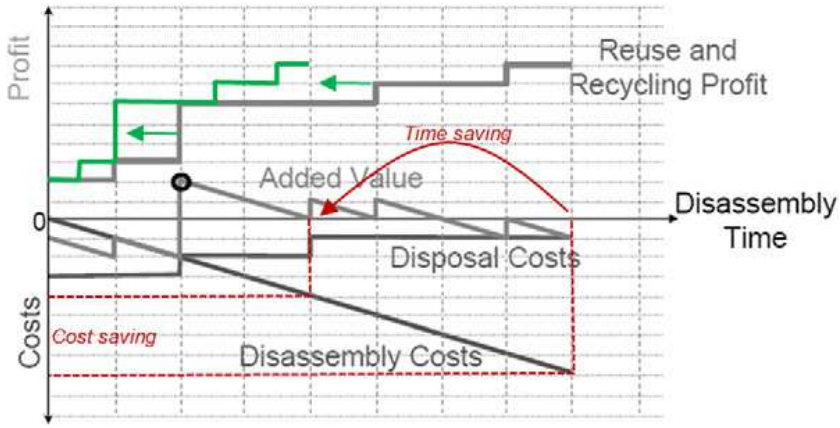


Figure 12 - Reduced disassembly time (source: Santini et al., I).

Besides Design for Disassembly measures, also the application of Design for Recycling principles can lead to a much more valuable economic situation. First of all, designing a vehicle with few and mono-material parts leads to ELV fractions with a higher material purity, stimulating dismantlers to remove mono material parts. In general, material fractions with a higher purity achieve higher profits on secondary raw material markets. Thus, the Reuse and Recycling Profits function is increased for each fraction dismantled. Moreover, since no liberation and separation processes are required, the final Recycling Rate is certainly improved due to the fact that none of these process is 100% efficient.

The economic effect of DfR is shown in Figure 13.

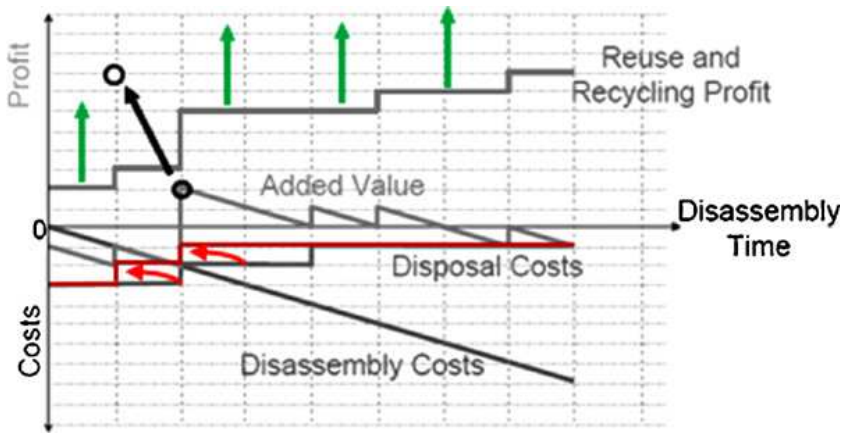


Figure 13 - Enhanced optimal disassembly depth for a product (source: Santini et al., I)

The generic EOL Cost function is reported along with the effect of increasing Reuse and Recycling Profits. Furthermore, the Disposal Costs are weight-dependent, thus increasing the mass of pre-treated and dismantled parts leads to a reduction of Disposal Costs (from gray to red line). Combining the effects of increasing Reuse and Recycling Profits and at the same time reducing Disassembly Costs and Disposal Costs, will increase the Added Value of the whole process and, therefore, explore the full benefits of DfD and DfR activities. In one concept: "*more with less*".

Finally, it results that a disassembly cost reduction of a factor 3, currently reported as about 300€ /ELV (GHK/BioIS, 2006), may cause huge savings when considering that more than 10 million end-of-life vehicles per year must be managed correctly.

As a result, dismantling is highly design-dependant. The application of a Design for Recycling (DfR) software showed that removing bumpers, fuel tanks, tyres and glass could lead to a theoretical 84.3% ELV Recycling, if materials are fully recycled, and glass removal will enhance ASR Heat Value at the same time. These materials may be removed during the pre-shredding activities. Particularly, during draining the ELV is left leaking into dedicated tanks for around 30 minutes. During this time, bumpers could be easily removed (also in a faster, destructive way) to recycle polypropylene. Concerning future vehicles material breakdown, if plastic content grows as it is estimate (GHK/BioIS, 2006), it will be necessary to create markets for recycled polymers in order to avoid the inevitable disposed or incinerated material increasing, as well as to save raw materials.

ELVs Directive claims for ecodesign application into new vehicles. Recycling targets were set in 2015 by Directive 2000/53/EC in view of the fact that an ELV is a 12-15 years old vehicle [Kanari et al., 2003], and consequently year 2000 new vehicles are 2015 ELVs.

Ecodesign itself was born in response to a problem: *How to develop a "green product"?*

There was a lack of knowledge in product Life Cycle, and Ecodesign, that at the beginning was known as Life Cycle Design, started to study all product Life Cycle. Then it considered, at the earlier design stage, all Life Cycle impact and once targeted product's critical performances, it redesigned a new product with technological innovation, triggering an "all Life Cycle enhanced performance" effect.

Applying this concept to ELVs, Ecodesign should now try to answer to the following questions:

How to achieve 85% of recyclability, if metal content is decreasing in new generation vehicles?

Nowadays vehicles are recyclable at about 65-70%, where will the 15-20% missing come from?

Both answers to those questions will lead to enhance the "non metallic" fraction EoL performances. Theoretically, improving new vehicles dismantling easiness and speed, in addition to the develop of captivating markets for recycled materials, will bring Directive 2000/53/EU targets economically feasible to achieve. But material choice has an equal importance since the single Designed for Dismantling part should be mono-material or properly compounded of easy-separable and recyclable different materials in order to achieve a secondary raw material flow. Avoiding, wherever possible, the use of dangerous chemicals and promoting green chemistry can help protect key resources like soil and water, and make others, like materials, safer, easier and less costly to recycle and reuse. The approach to chemicals management promoted by fully implementing REACH will help identify opportunities for substituting dangerous chemicals with safer and technologically and economically viable alternatives (EC, 2011).Furthermore even with the best DfD techniques there will always be some non-economically dismountable part and it will become shredder residue. Thus, hazardous substances must be avoided. Since the key aspect to apply design for recycling is the knowledge of recycling processes, and often designers are not expert in the field, the candidate would like to awaken to car producer to integrate recycling experts in the design and developing team.

The Italmetalli shredding plant

Gruppo Fiori holds two shredding plants: Italmetalli in Bologna and Italferro in Rome. It is one of the largest Italian operators and the two plants are able to treat about 250.000 ton per years of ELVs and other scraps, producing 180.000 ton of ferrous material, 6.000 ton of non ferrous metals and about 64.000 ton as the sum of light and heavy Fluff. Gruppo Fiori can process about the 20-25% of ELVs yearly produced in Italy.

At first, ELVs and other scraps are placed in a sheltered[2] scrap supply zone, where they are loaded inside a pre-shredder.

Figure 14- Shredder plant feeding material: ELVs and scraps, on the left, and separate collection, on the right

The pre-shredder task is to open the baled hulks by means of 2 crowns wheels rotating with two different angular speed. In that way the ELV is opened again and frayed. Crown tooth are distant enough to let the natural compressed gas (NCG) and liquid petroleum gas (LPG) tanks pass intact, so that the crane operator can sort them out. Thais is made to avoid that this kind of closed body enters into the hammer mill and explode inside of it. Pre-shredding operation allow to optimize the power consumption of the following shredding step since the material produced by this equipment is frayed and thick pieces can be easily removed. This lead to a constant power demand by the main engine and avoids current peaks. Now the scraps are ready to be size-reduced by means of the hammer mill. A general shredding plant layout is reported in Figure 15.

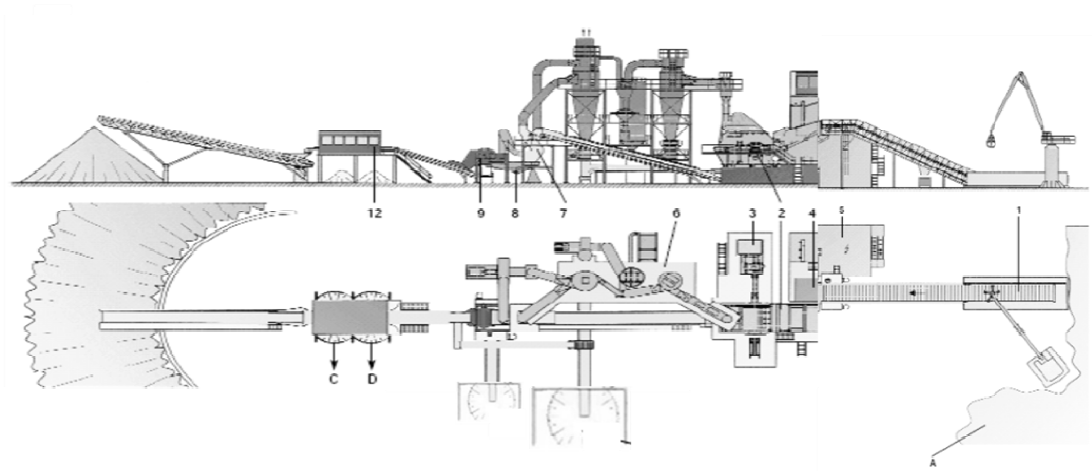


Figure 15- General shredding plant layout

[2] The covering of this waste is very important since wrecks can still contain oils and other fluids, which during a climate event could leak into the sewer burdening the water treatment plant.

From right to left the feeding material is loaded on a dedicated conveyor which lifts it to the hammer mill slide which is made of steel with a thickness of 100 mm. Here the material falls through the rotor and get pressed by the feed rollers (see Figure 16).

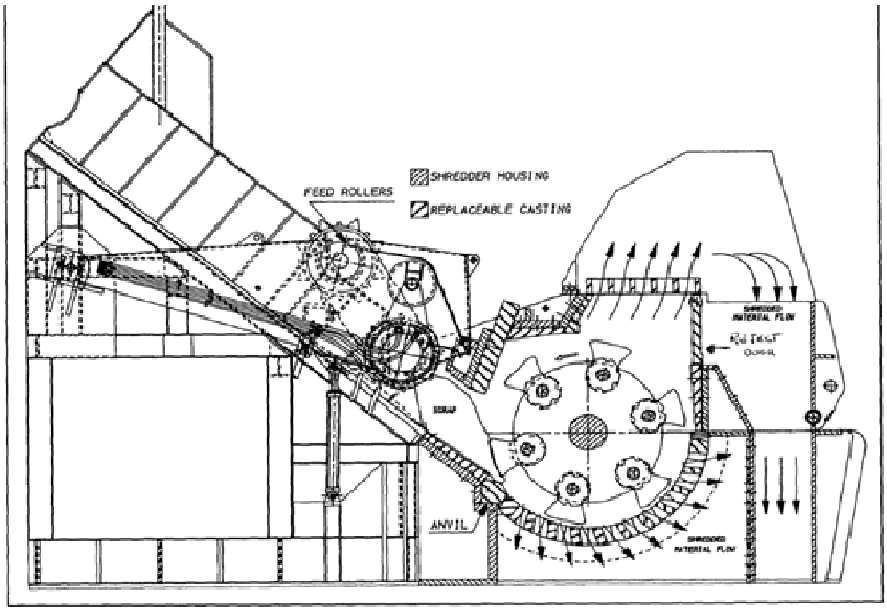


Figure 16 - Hammer mill

Once arrived at the rotor, the feeding material get broken by the hammers (see Figure 17).

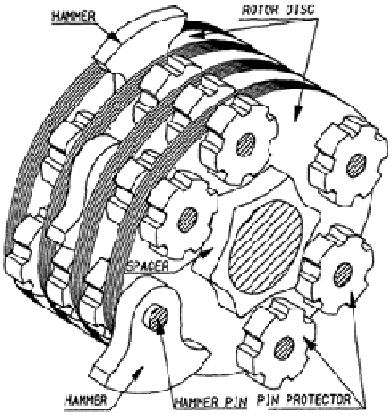


Figure 17 - Rotor

The main motor has 4000 HP power and it activates the rotor reaching an angular speed of about 600 rpm. Each hammer is about 500kg heavy and each one of the six shafts can contain up to three of them. The rotor cover can be opened for maintenance and replaceable castings contains high level of manganese to increase their duration. These castings are called “screens” and when a scrap piece is smaller than the holes, it can pass through, otherwise it continues to bang against the walls and the rotor until the proper size is achieved. A general overview of the shredding process is given in Figure 18.

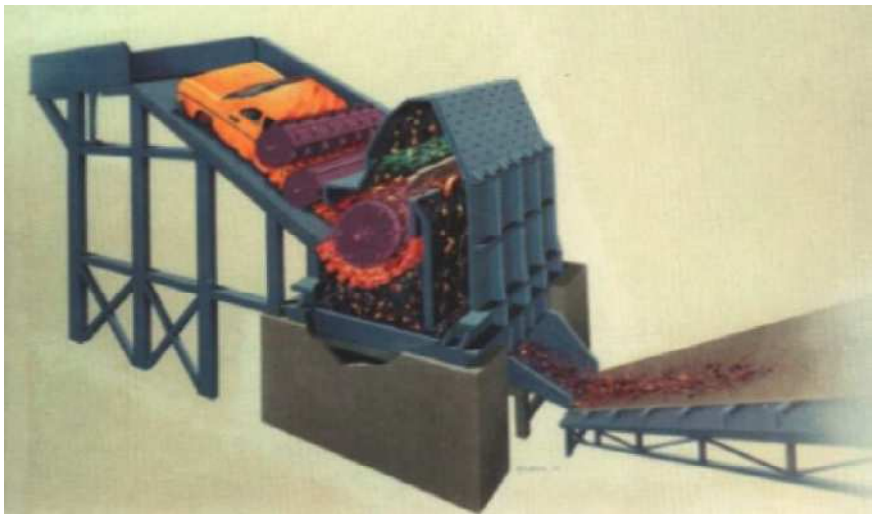


Figure 18 - General car shredding process overview

During shredding operation, fine particles produced inside the rotor are collected and this air flow is treated by means of a scrubber before its release into the atmosphere from the stack.

Then, all the residual pieces fall on a vibrating table and are conveyed to the air classifier in order to clean the ferrous product, also called *proler*, from the non ferrous materials (7, in Figure 15). At first, the light materials are sucked by counter-current air flow and collected outside as light shredder residue (Figure 19), while ferrous metals are sorted by other heavy materials by means of a magnetic drum (Figure 20).

Figure 19 - Light ASR output

Of course, separation is not perfect and *proler* needs to be refined by hand pickers, mainly because of animated rubber and starters (C/D, in Figure 15). Then, it is sent to Electric Arc Furnace steelmaking. There are two main routes to produce steel: the first route is called the “integrated route”, which is based on the production of iron from iron ore, while the second route, called “recycling route”, use scrap iron as the main iron-bearing raw material in electric arc furnaces. In both cases, the energy consumption is related to fuel (mainly coal and coke) and electricity. The recycling route has a much lower energy consumption

(about 80 %). Current energy consumption for the integrated route is estimated to lie between 17 and 23 GJ/t of hot-rolled product (SET-Plan, 2010). The "recycling route" converts scrap iron in electrical arc furnaces. Current energy consumption for this route is estimated to lie between 3.5-4.5 GJ/t of hot-rolled product (SET-Plan, 2010). Part of the steep decrease in energy consumption in the European industry over the 40 years (by about 50 %) has been due to the increase of the recycling route at the expense of the integrated route (the share has increased from 20 % in the 1970s to around 40 % today). However, a prospective shift to recycling is confined by scrap availability and its quality (JRC, 2011). Exploiting the advantages of following the recycling route (an order of magnitude lower of direct CO2 emissions than the integrated route), shredding industry is key in 2020 European Commission's carbon dioxide reduction targets achievement.

Figure 20- Magnetic drum (source: courtesy of SGM-Gantry S.p.A.) separating ferrous metals from heavy residue "misto gomma"

Figure 21- Proler

Non-ferrous heavy materials are called "*misto gomma*" (Figure 22) and transported to a dedicated treatment plant (see Figure 23).

This plant consists of a rotating drum and a cascade of sorting equipments such as magnetic pulleys, eddy current separators and inductions sensor sorting machines. Post-shredder technologies (PTSs) are treatments aimed at metals and other recyclables recovery from ASR. PSTs are divided in thermal-based

and mechanical-based technologies, both reported more in detail in the POST SHREDDER TECHNOLOGIES (PSTs) chapter.

Figure 22 - Non-ferrous heavy materials (so called "*misto gomma*") and a detail, on the right

At first, the heavy fluff is loaded into a hopper and through a conveyor belt on a rotating drum sieve (*trommel*).

Figure 23 - Heavy fluff treatment plant feed section

Then, each size fraction passes through an eddy current separator, ECS, to sort non-ferrous metals, loaded by a conveyor belt with a magnetic pulley at its end to remove ferrous metals. ECS, by means of an high frequency changing magnetic field, can induce eddy currents into conductive metal pieces. These currents have their own magnetic field opposite to the ECS one, so conductive pieces are diverted from the inert natural trajectory (see Figure 24).

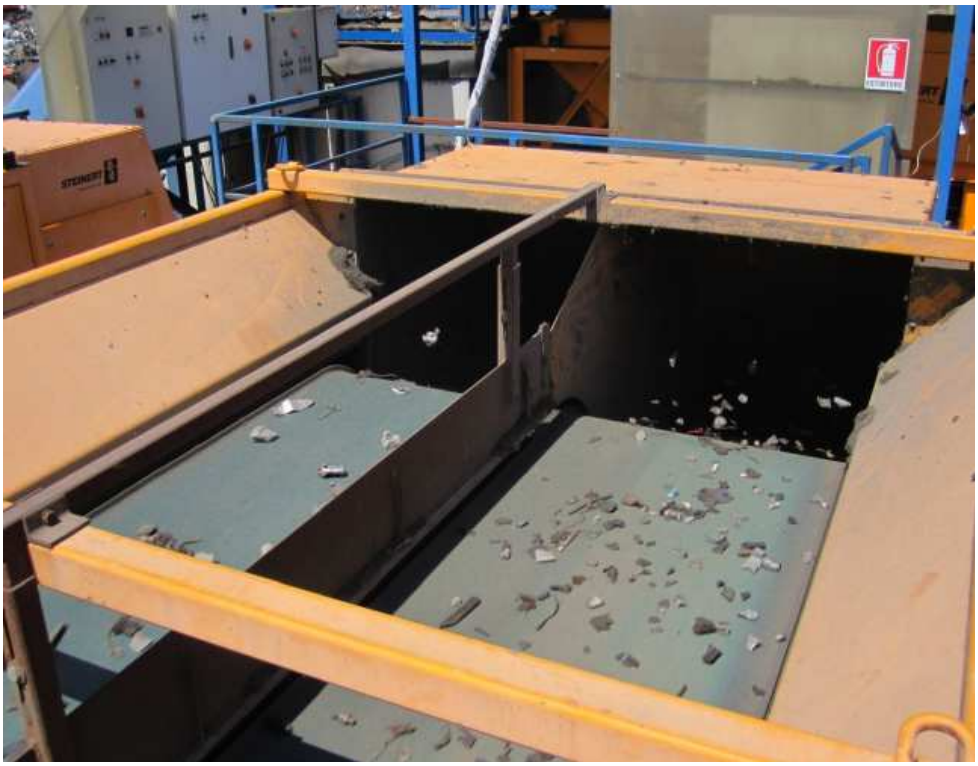


Figure 24 - ECS separator in action

All the materials that the eddy current machines are unable to separate are also called "*negative*". This flow is mainly made of rubbers and heavy plastics but it contains also a certain fraction of stainless steel, copper wires and non ferrous materials escaped from the ESC itself. This residual flow is treated by the induction sorting system (ISS) which can detect the residual metals and, by means of a compressed air shot, sort them from the rubbers and plastics.

Figure 25 - ISS in action

Stainless steel, non-Fe metals, printed circuit boards and copper wires which have been sorted by the ISS are conveyed to a vibrosort and then to manual separation cabin. In the end, the residue heavy ASR (Figure 26) is put together with the light ASR and sent to the dedicated landfill property of the Gruppo Fiori.

Figure 26 - Heavy ASR

The mass balance at the shredding plant is reported in the following figure:

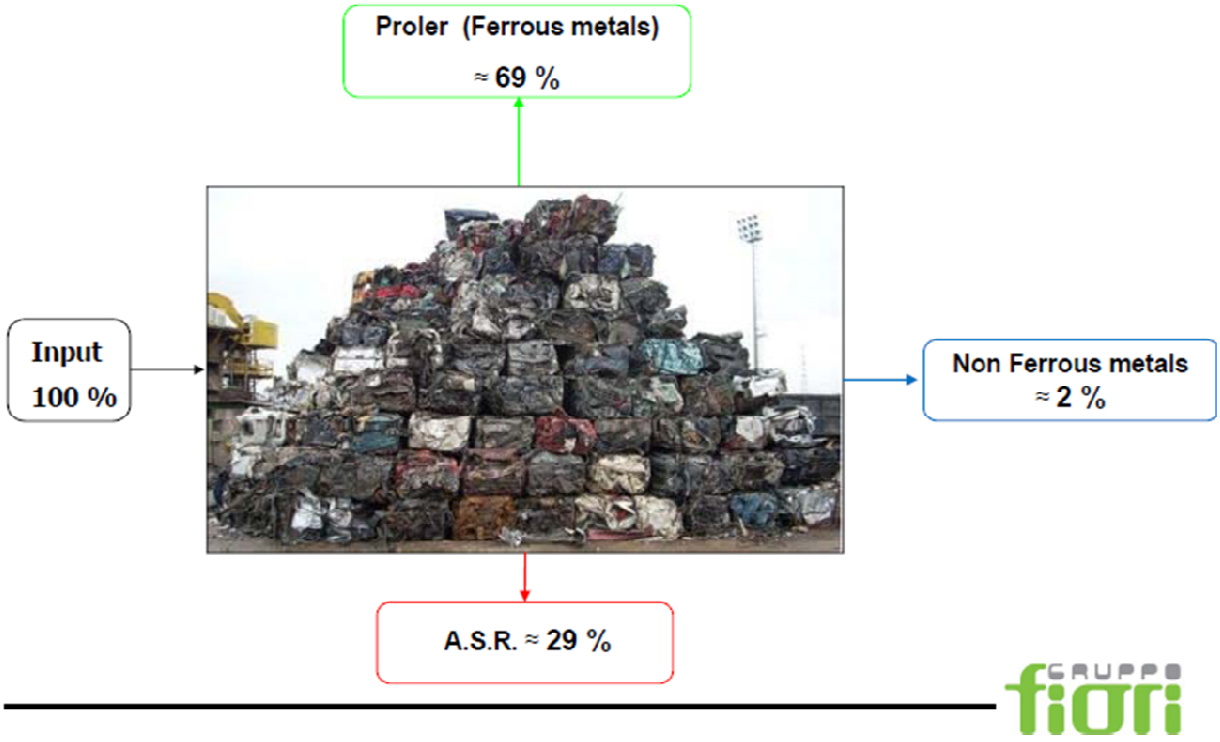


Figure 27 - Shredding plant mass approx. mass balance

This waste still contains valuable metals and one among the aims of this work is to reduce the metal losses. At present, a new heavy fluff treatment line is under development and design. All the machineries involved have been tested and mass balances and efficiencies at each step calculated. In fact, even though Gruppo Fiori possess a landfill dedicated to ASR disposal, research is addressed to further metal recovery from ASR, to improve the products quality and to find new management solution for ASR such as thermal recovery.

Aim of the thesis

The principal aim of this Ph.D. thesis is to apply *industrial ecology* principles into end of life vehicles management.

One more specific goal is to prove the importance of end-of-life vehicles (ELVs) de-pollution and dismantling in improving Italian recycling rate, by reporting a dedicated national ELVs recycling campaign.

In particular, automotive shredder residue (ASR) recycling has been studied. Tools such as *life cycle assessment* and *ecodesign* have been adopted to prevent waste production itself and to identify the most sustainable ASR treatment scenario.

LCA results have been the compass for applied industrial research in the ELVs shredding field. Innovative metal sorting technologies have been studied, developed, tested and finally installed in the plant. The targets were both to reduce the metal losses at the shredding plant and to reduce the material disposed in landfill.

This study incorporates also the ASR energy recovery assessment via pyrolysis and thermodynamic cracking as an alternative to traditional co-incineration with MSW. Along with material recycling, *waste to energy* is one of the industrial symbiosis opportunity to reduce the use of landfill disposal in ASR management.

Finally, during these three years, the candidate aspired to both comprehend the logical sequence of treatments which are useful to completely remove metal from ASR, and to design and develop innovative treatment lines with an almost "*zero landfill*" target.

THE AUTOMOTIVE SHREDDER RESIDUE (ASR)

The background chapter shall enable the reader to comprehend both the European Commission's aims together with needs that inspired ELVs Directive creation, and the state of the art of both ASR production and management. In this chapter, the main actor of this thesis is analyzed deeply by reporting two experiences the candidate carried out during the first PhD year. Both these two works lead to a publication reported in Appendix II and Appendix III, respectively. In this thesis, a short summary of these publications is reported along with personal remarks.

Italian Trial

Italy is a very picturesque country in which huge differences in citizens' behaviour exist from North to South and the habit of doing things "*like they have always been done*" usually prevails new EU Directives and the EU Commission's legislation. This trial was conceived as a reaction to the poor result of Italian recycling rate (RR) in 2006 - 70.3% -, in order to verify the effectiveness of this regrettable performance (Santini et al., III). Usually, it takes around 3 years for the EU Commission to collect and elaborate all the data concerning ELVs yearly state of the art, thus it was late 2007 when the trail campaign was decided. One of the hypothesis at the basis of recycling failure was the lack of standardized procedure for dismantling, mainly due to the considerable geographical variation in Italy, both in the adopted procedures and technologies. Practically, many operators were not filling-in correctly the dedicated modules for yearly mass balance (when not reporting at all).

This trial, which met an urgent request from the stakeholders of the ELV supply chain, has been performed in order to determine the actual Italian ELV recycling rate, particularly focusing on component dismantling and reuse share. A sample of 630 ELV has been taken to enhance the reliability of results. Such significant number turns this trial into the largest European scientific experiment in the ELV management sector and the first example in Europe in which Public Institutions and Economic Operators of ELV waste management cooperate actively. As a consequence, a shredder campaign trial designed and developed by FIAT, University of Bologna – Rimini branch, Italian Environmental Protection Agency (ISPRA) and Italian shredders and dismantlers Associations has been carried out during March 2008.

Figure 28 - the candidate (on the right) and the other delegates during the trial

All the vehicles had been chosen to form a representative sample of the overall amount of cars shredded in Italy in 2006 as far as age, engine type, brand and model is concerned. To process all the vehicles in a single working day in the shredder plant, the total amount of vehicles has been set to 630. In particular, as for

vehicle selection during sample design, the first 500 most de-registered vehicles in 2007, separated according to brand and engine type, were the ones chosen first. Afterwards, each vehicle class has been proportionally weighted, in order to create the final 630 ELV sample. Not every vehicle type dismantled in Italy was found, but the final sample represented 1,069,797 ELVs, corresponding to 83% of the total amount of 1,354,205 ELV actually shredded in 2006.

This experimental campaign involved 18 independent dismantling plants. They were chosen to be representative of the Italian recent scenario, as they refer to both spatial distribution, with 3 macro-zones: Northern, Central and Southern Italy, and company dimension (small, medium and big enterprises).

Figure 29 - Dismantling plants involved in the Trial (source: Di Carlo, 2008)

Each vehicle, through its components and materials, was checked in the course of the trial by filling-in proper forms. Dismantlers had to remove all fluids, big mono-material components, such as bumpers and windscreens, and all the components with a market price, so far potentially reusable. The process of giving each vehicle and each removed component a progressive number, made possible to code unambiguously both the dismantler and the vehicle.

Figure 30 - baled hulk classification

Thus, during pre-treatment and dismantling, the involved operators had to weight and classify all the removed materials and components, reporting every step. After that, the remaining hulks were baled and carried to the chosen shredder plant with dedicated lorries.

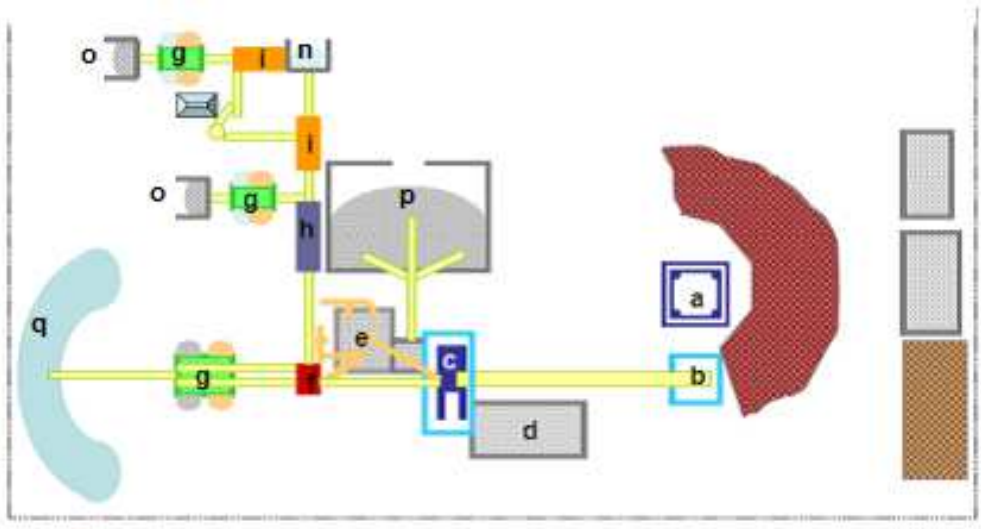


Figure 31 - CRS (Leinì, Turin) shredding plant used during the trial flowsheet.

LEGEND: a) crane, b) pre-shredder, c) hammer mill, e) air treatment section, f) magnetic drum, g) hand pickers, h) trommel, i) eddy current separator, n) non-ferrous metals, o) heavy fluff, p) light fluff, q) proler.

The resulting 80.8% recycling rate is higher than the one stated in the target of Directive 2000/53/EC for 2006 - equal to 80% -, but differs from official data available on Eurostat website for 2006 (70.3%), because the result of this trail is almost the best that standard Italian ELV treatment procedures can potentially reach without any ASR treatment by PSTs.

On the contrary, recovery rate target, equal to 85%, has not been achieved, due to the structural weakness of the Italian incineration plant framework. ASR still contains 8% metals and 40% potentially recoverable polymers. Nevertheless, to reach the 85% recycling and 95% recovery rate in 2015, the implementation of innovative and economically sustainable material and energy recovery processes from car fluff appears inevitable. In any case, even though chemical–physical analysis revealed car fluff Lower Heat Value (LHV) to be greater than the limit imposed by Directive 1999/31/CE (LHV P13,000 kJ/kg), due to the lack of industrial alternative to landfilling, in Italy this deadline had been postponed to 28 February 2010. Moreover, some parameters such as ashes, chlorine, cadmium and lead content, exceed Italian limits for Refuse Derived Fuel making this waste particularly hard to manage.

Finally, it is important to highlight that by avoiding cross-contamination of hydrocarbons and mineral oils during the shredding step, dismantling and fluids removal steps revealed to be fundamental operations. Thus, by signing the national “Agreement Framework Programme on the ELV Management” stakeholders made sure the mandatory ELVs de-pollution and dismantling operations were carried out. Moreover, this trial provided information about the parts of the vehicles that could not be easily removed or sorted from the rest; this was a crucial suggestion for manufacturers, since they could implement an ecological design policy, in order to curb the amount of unrecoverable shredder residue.

Trial results

After shredding process conclusion and heavy ASR floatation, all the resulting materials have been collected and weighted. Then, data have been gathered and elaborated.

Pre-shredder treatments mass balance is reported in Figure 32, as follows.

Treatment	*Mass (ton)*	*% on the total*
Total input (M_V)	577.0	100
De-pollution (M_d)	17.2	3.0
Fluids, 5.7 ton; fuel, 3.5 ton; batteries, 6.9 ton; other, 1.1 ton		
Components dismantled for reuse (M_{re})	51.4	8.9
Components dismantled for recycling (M_{rcy})	55.3	9.6
Tyres, 16.6 ton; glass, 12.0 ton; plastics (bumpers, tanks, etc.) 9.1 ton; other metallic components, 19.5 ton		
Total pre-shredder	123.9	21.5
Remaining hulks	453.1	87.5

Figure 32 - Pre-treatment operations mass balance (source: Santini et al., III)

Dismantling for reuse ratio is strongly input-dependent and it is related to the market demand for spare parts, to the ELV age and to consumers' behaviour. Main targets of this step are door panels, driving mirrors, lights and other working devices. This result reflects Eurostat data, according to which Italy is at the first place among European Member States concerning the total mass of components dismantled for reuse in 2006 and 2007 (Eurostat, 2011).

Figure 33 - dismantled for reuse components (door panels and rims)

Dismantling for recycling works in a slightly different way, because it focuses on removing mono-material or easy to recycle components for further material recycling, thus this step may involve destructive dismantling for reducing time and consequently costs. A particular recommendation of the trial was to pay a particular attention to the removal of these components (namely bumpers, catalytic converters, tyres and windscreens), which would significantly improve the overall dismantling performance, if correctly recycled.

Figure 34 - dismantled for recycling materials (windscreen and bumpers)

Once the 630 vehicles arrived at the shredding plant, shredder campaign began.

Figure 35 - shredding campaign feeding material

All material streams at the shredder plant have been weighted at each collection point. Results of the shredding trial (Figure 36) are in line with those found in literature, considering both ELV input composition and machinery efficiency (Ferrao et al., 2003; Jody and Daniels, 1991; Kanari et al., 2003; Forton and Harder, 2006; Nourreddine, 2007; Srogi, 2008).

Material	*Mass (ton)*	*% on the total*
Light fluff	90.5	20.2
Ferrous metals (M_{Fe})	323.4	72.1
Non-Fe metals (M_{nFe})	18.6	4.1
Heavy fluff	15.1	3.4
Loss	1.1	0.2
Total Shredding Input	448.7	100

Figure 36 - shredding campaign results (source: Santini et al., III)

Figure 37 - proler produced

Ferrous metals, which account for 72.1% of total shredded material, are sent to foundries to be recycled in electric arc furnaces resulting in cast iron products. Non-ferrous metals (mainly aluminium, brass and

copper) are sent to smelters to be recycled. Metal recycling is very cost-effective, due to metals value and sorting easiness.

Figure 38 - ASR production during trial

Car fluff composition was: 17% fines, 8% metals, 1%wood , 23% plastics, 15% foam rubber, 9% rubber and 27% textiles.

ASR composition may vary strongly depending on the shredding input mix (vehicles, white goods and ferrous waste combinations) and on the de-pollution and dismantling operations carried out. In this case, input was a statistical sample shaped for a properly designed experiment and de-pollution and dismantling operations were applied carefully.

Fines form 0–20 mm fraction, which contains small particles that cannot be clearly identified. From a direct observation it contains also some small pieces of glass but it has not been possible to separate them. Few larger pieces have been found as well, but their amount over the total mass is negligible.

This waste still contains up to 8% of metals and up to 40% of plastics (both soft and hard) and polyurethane foam (PUF) that could be separated and treated for enhancing material recycling with post shredder technologies, PSTs.

Italian 2008 recycling rate

$R_{cyc} = (M_d + M_{re} + M_{rcy} + M_{Fe} + M_{nFe}) / M_v = 80.8\%$ [3]

Italian recycling rate assessed by this trial is equal to 80.8%; the difference can thus be quantified in more than 10% of increased recycling rate, compared to the previous report. Consequently, it comes out that 19.2% of an ELV is currently destined to landfill.

According to Eurostat (Eurostat, 2009), almost 370,000 ton of fluff are landfilled every year in Italy, since incineration has not been applied to this waste stream yet, except for a few pilot scale plants.

[3] Where M_l = loss; M_d = de-pollution; M_{re} = reuse; M_{rcy} = recycling; M_{Fe} = ferrous metals; M_{nFe} = non-ferrous metals; M_v = vehicle input weigh.

Conclusions

This trial, which met an urgent request by the stakeholders of the ELV supply chain, has been performed in order to determine the real Italian ELV recycling rate, particularly focusing on component dismantling and reuse share. A sample of 630 ELV has been taken aiming at enhancing results reliability. Such significant number turns this trial into the largest European scientific experiment in the ELV management sector and the first example in Europe in which Public Institutions and Economic Operators of ELV waste management collaborate actively.

The resulting 80.8% recycling rate is higher than the Directive 2000/53/EC target for 2006, equal to 80%, but differs from official data available at Eurostat website for 2006 (70.3%), since the result of this trail is almost the optimum potentially obtainable by standard Italian ELV treatment procedures without any ASR treatment by PSTs.

On the contrary, recovery rate target, equal to 85%, has not been achieved due to the structural weakness of the Italian incineration plant framework. ASR still contains 8% metals and 40% potentially recoverable polymers. Nevertheless, in order to reach the 85% recycling and 95% recovery rate in 2015, the implementation of innovative and economically sustainable material and energy recovery processes from car fluff appear unavoidable. In any case, even though chemical–physical analysis revealed car fluff Lower Heat Value (LHV) to be greater than the limit imposed by Directive 1999/31/CE (LHV P13,000 kJ/kg), due to the lack of industrial alternative to landfilling, in Italy this deadline has been postponed to 28 February 2010. Besides, some parameters, namely ashes, chlorine, cadmium and lead content, exceed Italian limits for Refuse Derived Fuel making this waste particularly difficult to manage.

Finally, it is important to enlighten that by avoiding cross contamination of hydrocarbons and mineral oils during shredding step, dismantling and fluids removal steps revealed to be crucial operations. Thus, by signing the national ‘‘Agreement Framework Programme on the ELV Management” stakeholders ensured the mandatory carrying out of the ELVs de-pollution and dismantling operations. Moreover, this trial provided information about the parts of the vehicles which could not be easily removed or sorted from the rest; this was an important suggestion for producer since they could implement an ecological design policy, in order to limit the amount of unrecoverable shredder residue.

ASR characterization

At the Gruppo Fiori shredding plants, regularly dedicated trials are performed in order to assess plants' efficiency, mass balance and metal losses through the analysis of ASR composition. In fact, ASR still represent a waste, thus a loss of materials, and to check its composition is important in order to understand the working condition of the plant itself.

Many factors combine to increase the interest for this waste:

– treated ELV volume (around 10 million tons/year in Europe rising to 14 million tons/year by 2015). This volume is actually reducing, thus a higher sorting efficiency and metal recovery is important for being competitive.

– recyclable materials content (such as plastics and residue metals),

– high heat value (more than 13 MJ/kg), for thermal recovery

– its potential hazardousness due to the presence of oils, hydrocarbons, PCBs and heavy metals, especially in view of the coming into force of Italian Legislative Decree D.lgs. 205/10, that introduced the Ecotoxicological Characterization of Waste (so called "H14").

Sampling procedure

For five consecutive working days, a dedicated vehicle shredding trial was performed and samples of about 125 kg each were daily collected from the light fluff output flow, by means of a compact excavator. Samples were stored into a tank till a final weight of about 650 kg. A suitable cover was applied in order to avoid the exposition to possible rainy events.

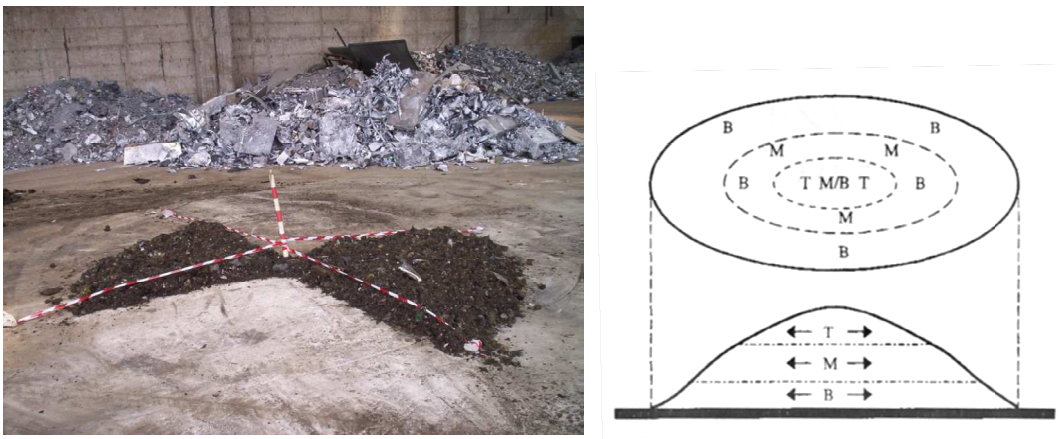


Figure 39 - Quartering procedure sample

The accumulated material was then subjected to a quartering procedure, according to a standardized methodology (Italian norm UNI 10802:2004, Figure 39). The latter operation was performed four times, in order to obtain a final sample of about 16–18 kg.

Five size categories were considered: one referring to the whole material, and the other four identifying different ranges, suitable to obtain more precise characterization. The four fractions were chosen as follows: 0 - 20 mm; 20 - 50 mm; 50 - 100 mm; > 100 mm.

For each coarser fraction, physical–chemical and material-type analysis were performed according to official methods reported by Italian Environmental Protection Agency (ANPA, 2002; APAT, 2008).

The composition analysis results from the sum of the different material categories in each size fraction. However, 0–20 mm fraction has been considered simply as ‘‘fines” because it was impossible to correctly allocate each minute piece to a single category.

Moreover, despite their significant share on the total mass, fines are currently not considered for recycling, due to complexity of their composition.

As for physical–chemical analysis, some kilograms of samples material were powdered, homogenized, and quartered in order to obtain representative aliquots of about 500 g. On the resulting material, chemical–physical analysis was performed as follows:

– Humidity and ashes: according to standard procedures, moisture was calculated as the relative loss in weight after drying at 105°C (UNI 9903-7:2004); whereas ash content was determined as the residue of incineration at 575 °C (±25 °C), reported in percentage of the initial material (UNI 9903-9:2004).

– Lower and upper heating values (LHV/UHV) were determined by means of a bomb calorimeter (UNI 9903-5:2004).

– Heavy metals (As, Cr, Mn, Ni, Pb, Cu, Cd, Hg, and Se) were determined by atomic absorption spectrophotometer after HCl/HNO_3/HF digestion. Mercury was analyzed using the cold vapour technique. Pb-volatile was determined as the difference between total Pb and its content in ashes (UNI 9903-13:2004).

– Sulphur and chlorine determination was carried out in two steps: combustion of the sample in a bomb containing oxygen under pressure and collection of chloride and sulphate in an absorption solution; analysis of Cl and S was performed by ion chromatography (CEN/TS 15408).

– Organic chlorine was determined as the difference between total and soluble chloride, after aqueous extraction.

– Mineral oils: samples were treated with Freon 113; extract was eluted through a column filled with Florisil adsorbent, collected and evaporated, calculating the content by a gravimetric analysis (CNR-IRSA, 1985).

– PCBs and PAHs were determined by GC–MS analysis, after an extraction with a mixture n-hexane/acetone and a chromatographic purification (silica gel and alumina) (US EPA, 2007).

Physical-chemical and commodity analysis

A composition analysis was performed on the fluff samples in order to study ASR for future thermo-chemical and separation trials. As it can be easily observed in Figure 40, fines (0‑20 mm fraction) represent almost a half of the total sample.

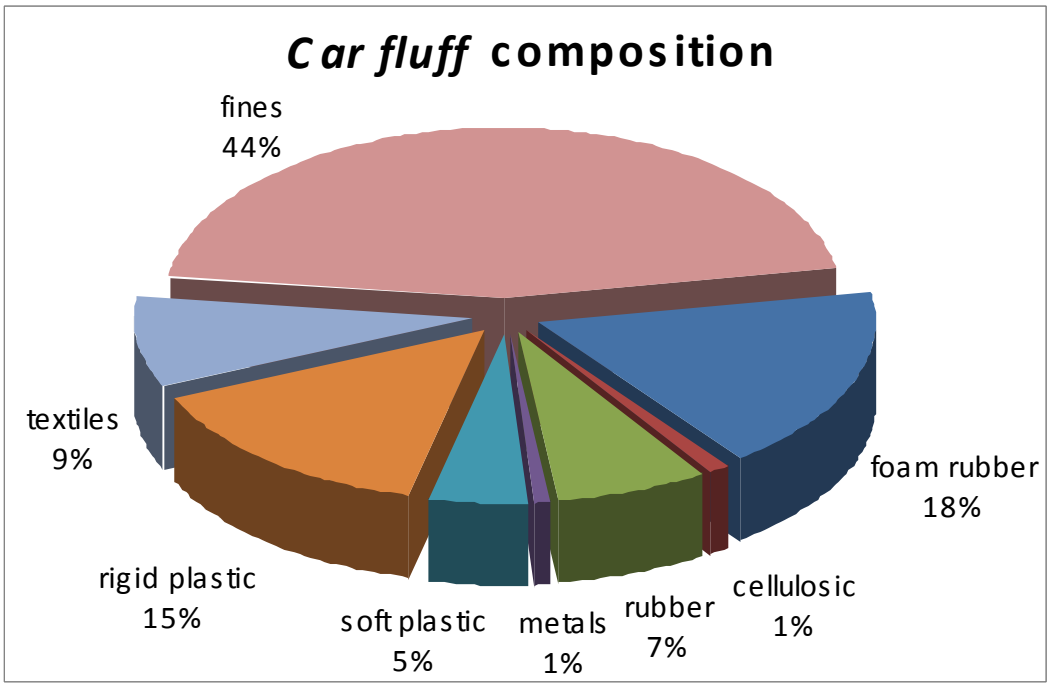


Figure 40 - car fluff commodity analysis

For the fine fraction, a thorough composition analysis cannot be performed, because of the very small size of the materials included. Anyway, it is possible to identify glass pieces, plastics and metals, blended together with dust and dirt.

The remaining fluff mainly consists of polymers, up to 48%, such as polyurethane (foam rubber), plastics and rubbers. Textiles account for about 10% on the total and together with polyurethane foam (PUF) are strictly related to car seats and carpeting. The dismantling and recycling of these components (e.g., by using textiles as dewatering agent and recycling PU with proven technologies according to GHK/BIOIS, 2006 and to Nourreddine, 2007) may lead to a rough 30% ASR mass reduction; the importance of car seat dismantling has been already discussed elsewhere (Santini et al., 2010), but it may be useful to observe that the density of PUF blocks is very low, forming a greater share of the total ASR volume despite their mass, thus influencing fluff transportation costs. Metals and paper/wood account for 1% each, but a larger amount of metals likely lies in the fine fraction. These results are in line with some works reported in international literature (Nourreddine, 2007; Forton et al., 2006; Kanari et al., 2003). Anyway, due both to the great variability and to the lack of a standard categorization method, it is difficult to characterize unambiguously some ASR features, especially concerning the size limit of fine fraction and plastics classification (Harder and Forton, 2007).

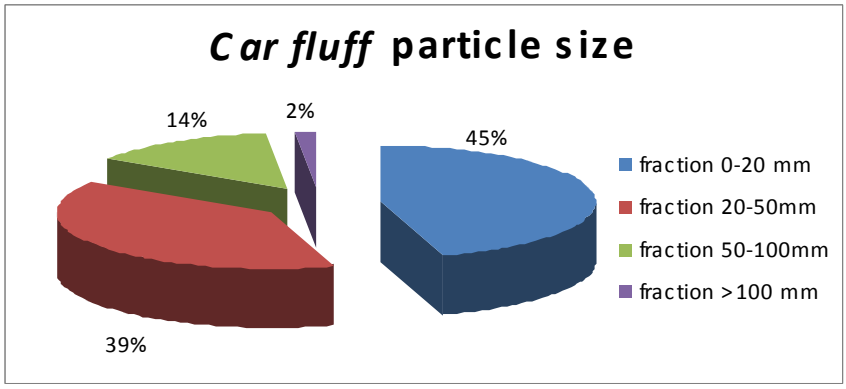
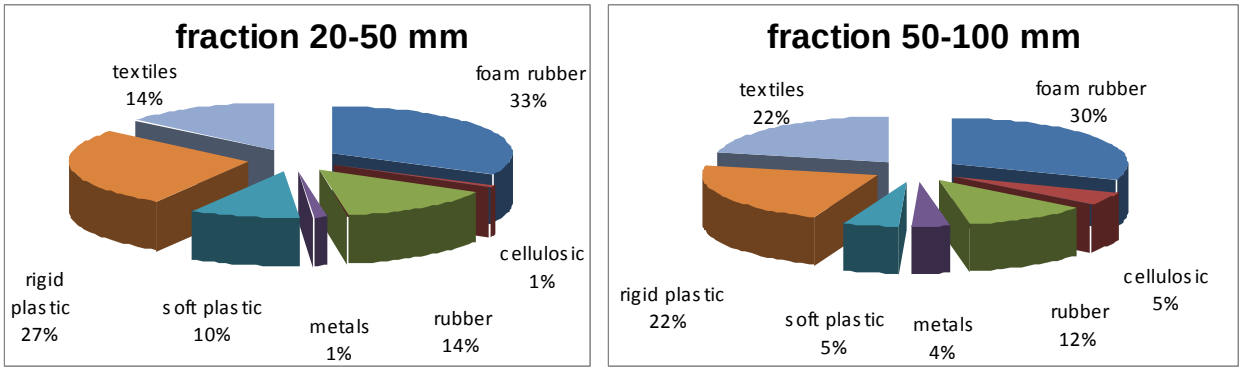


Figure 41 - Car fluff size distribution

ASR size distribution is reported in Figure 41. More than 80% of the ASR results in a size smaller than 50 mm while only 2% of it is made of pieces larger than 100 mm. The latter fraction is mainly composed of large PUF blocks and plastics that probably bended without crushing when passing through the hammer mill. Considering this information, sieving looks like a fitting solution to pretreat ASR for further separation or thermo-chemical processing of specific fractions. The sieving of this material is usually carried out in large rotary screens because of their robustness and relative insensitivity to choking (Dalmijn and De Jong, 2007).



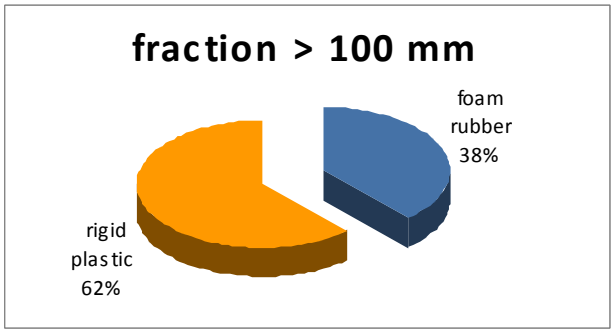


Figure 42 - ASR size fractions commodity analysis

Coarser fractions composition has been finally investigated and results are reported in Figure 42. Fractions 20-50 mm and 50-100 mm are rich in polymers. Plastics, rubber and foam accounts for more than 70% of the total. Textiles and cellulosic lies mainly in the 50-100 mm fractions. It is interesting to notice that metal percentage amount in the composition of 50-100 mm fraction is at least four time higher with respect to the other categories. This is mainly due to copper wires and aluminum content and this could suggest an interest in developing machineries for further separation. Fraction >100 mm is made of large pieces of

plastics and foam rubber which have not been broken during the shredding process. Even if its composition is not as various as the other fractions, low ashes combined with high LHV suggest a good energy recovery potential. It is interesting to notice that metal concentration in the 50-100 mm fraction is four time higher with respect to other categories. This is mainly due to copper wires and aluminium content which may lead to further plant machinery development.

Parameter	*U.M.*	*Original sample*	*Italian RDF limits*	*Fraction 0<φ<20 mm*	*Fraction 20<φ<50 mm*	*Fraction 20<φ<100 mm*	*Fraction φ>100 mm*
Humidity	%	10	*25*	13.8	4.4	13.9	1.3
Ash	% *d.w.*	28.2	*20*	40.4	16.4	24	2.5
LHV	kJ/kg	13800	*>15000*	10700	15200	18700	23800
UHV	kJ/kg	15000	-	11700	16400	20000	25900
Mineral oils	mg/Kg	26800	-	32800	23000	18000	22100
Chlorine	%	< 0.05	*0.9*	<0.05	<0.05	<0.05	<0.05
Organic Chlorine	mg/Kg	16.4	-	6.7	28.7	13.1	22.4
S	%	0.12	*0.6*	0.15	0.10	0.09	0.08
As	mg/kg *d.w.*	16	*9*	16	20	9	11
Cr	mg/kg *d.w.*	300	*100*	270	390	170	360
Mn	mg/kg *d.w.*	880	*400*	1220	660	460	500
Ni	mg/kg *d.w.*	210	*40*	230	210	140	170
Pb	mg/kg *d.w.*	4000	-	3800	5000	2000	2000
Pb-volatile	mg/kg *d.w.*	3700	*200*	3500	5000	1100	1900
Cu	mg/kg *d.w.*	27	*300*	34	16	30	42
Cd	mg/kg *d.w.*	14	-	6.7	7.0	5.6	4.6
Hg	mg/kg *d.w.*	0.80	-	0.65	0.90	1.02	0.87
Cd+Hg	mg/kg *d.w.*	14.6	*7*	7.4	7.9	57	5.5
Se	mg/Kg *d.w.*	<1	-	<1	<1	<1	<1
PCBs	mg/Kg *d.w.*	5.3	-	2.5	7.7	7.3	8.4
PAHs	mg/Kg *d.w.*	4.4	-	3.6	4.8	5.6	4.4

Figure 43 - Physical-chemical properties of car fluff sample, as a whole and in the different fractions.

Figure 43 reports the results of the physical‑chemical analysis made on the different fractions and on the original sample (as a whole), and a comparison with the limits fixed by the law for a material to be considered as refuse derived fuel (RDF).

Fines are the fraction with highest contents of ash and mineral oil. LHV increases with particle size while ash shows an inverse trend. This may be ascribed to dirt, soil, metals, glass and other incombustibles, making the finer fraction unsuitable for energy recovery processes. Furthermore, some heavy metals (As, Mn, Pb and Cd) are more concentrated in the finer fractions but, on the other hand, PCBs tend to distribute into the coarser fractions. Confronting the total sample with Italian RDF law limits (Ministerial Decree 05/02/ 1998) it is possible to notice that many parameters (namely: ash

content, LHV, AS, Cr, Mn, Ni, and Pb) do not meet the reference values; this is in line with other literature data (Genon and Brizio, 2008; European Commission, 2003). Anyway, concerning ashes and LHV, the screening of the finer fraction may lead to an overall improvement, since the higher values of the former parameter and the lower of the latter are found in the finest fraction.

Conclusions

The characterization of ASR produced in an Italian auto shredding plants leads to significant outcomes, from economical and environmental viewpoints: ASR consists of up to 40% potentially recyclable materials, with a high LHV (manly polymers).

Fine fraction, which amounts to about 45%, is characterized by a lower LHV and higher residual ashes, proving to be unsuitable for energy recovery. The coarser fractions (20–50, 50–100, and >100 mm) are rich in polymers, that may account for more than 70% of the total.

Anyway, due both to the great variability and to the lack of a standard categorization method, some ambiguities in the characterization of ASR remain, especially concerning fine fraction size limit and polymer classification.

The high LHV found in coarser fractions suggests that energy recovery is possible, even though the presence of many micro-pollutants exceeding the limits fixed by the Italian law for materials to be considered RDF, needs further pre-treatment operations. Anyway, in addition to energy recovery, incineration may be useful in destroying organic pollutants as PAH and PCBs. Moreover, it should be preferred to landfilling, according to the waste hierarchy reported in Directive 2008/98/EC on waste (EC, 2008).

In order to achieve the conversion of car fluff to RDF, pre-treatment by sieving appears a pursuable approach, since it could remove the fine fraction, the most critical one. Anyway, this management solution could not allow the attainment of Directive 2000/53/EC targets in 2015.

Thus, recycling processes, or other thermal technologies, as gasification and/or pyrolysis of the residue with a recovery of chemical building blocks, turn out to be necessary for the achievement of these targets (GHK/BIOIS, 2006).

ENVIRONMENTAL IMPACT OF ASR TREATMENTS

Life cycle assessment (LCA)

Once Italian ELVs recycling rate was identified, LCA has been used as an industrial ecology tool to compare environmental impacts of most common ASR treatment. This work has been used as a compass to define future investigations routes. European environmental policy is usually a beacon for other continents regulations, especially for US. Concerning waste, with the latest Directive 98/2008/EC, a new waste hierarchy is introduced:

a) prevention;

(b) preparing for re-use;

(c) recycling;

(d) other recovery, e.g. energy recovery; and

(e) disposal.

In Article 4.2 it states: "*When applying the waste hierarchy (...) Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life-cycle thinking on the overall impacts of the generation and management of such waste*" (EC, 2008). LCA approach, in the same Directive, is also explicitly considered, to assess the best treatment option from an environmental point of view. That's because Europe *wants to do the right thing, not just the things right*! (Hauschild, 2010) Thus, results shall indicate which fate shall ASR undergo to minimize environmental impacts.

The functional unit of this study takes into account 1 ton of ASR. Its material breakdown was divided into *plastics, metals, textiles, foam rubber* and *others*, with an average composition between the Italian Trial analysis results and the literature sources (Santini et al., 2010; Boughton & Horvath, 2006; Forton & Harder, 2006, GHK/BioIS, 2006).

Plastics	*kg*	*Metals and alloys*	*kg*	*Fines*	*kg*	*Textiles*	*kg*	*Rubber*	*kg*
ABS	33.6	Aluminium	70.0	Paints	56.0	Natural	65.0	EPDM	140.0
PP	86.4	Copper	4.4	Glass	42.0	Synthetic	65.0		
PE	19.2	Steel	5.9	Sand	42.0				
PUR	168.0	Iron scrap	26.5						
PVC	67.2	Lead	0.4						
PA	28.8	Brass	2.8						
Other plastics	76.8								
Total	*480.0*	*Total*	*110.0*	*Total*	*140.0*	*Total*	*130.0*	*Total*	*140.0*

Figure 44- ASR composition considered in this study

The study analyses four PSTs alternative to landfill. So far, the preliminary phase of the study consisted of a detailed analysis of the current techniques and technologies to treat car shredding residues. Such methods aim to recover matter and/or energy. As for energy recovery, the study focused on *incineration, pyrolysis* and *gasification.* Subsequently, based on ASR treatment "state of the art", five ASR treatment scenarios were identified and underwent a modelling with an LCA analysis. The scenarios listed in table 2 could be a potential alternative to landfill, especially to save non renewable resources and reduce disposal.

End-of-Life scenarios	*ASR treatment management*
Landfilling	ASR resulting from Italian Trial is disposed of in landfill.
Further metals recovery	Recovery of 60kg of metals from ASR and residue disposal.
Thermal treatment with energy recovery	ASR remaining after metal recovery by scenario 2, is burnt in co-combustion (5%) with MSW for energy recovery.
Advanced material recovery and incineration	Starting from scenario 2, ASR output is treated to separate plastic matters. The remaining fraction is incinerated for energy recovery.
Feedstock recycling	Starting from scenario 2, ASR output is subjected to a gasification process for the production of syngas, which is subsequently converted to methanol.

Figure 45 - ASR treatment scenarios

The first three scenarios are currently operating in Italy but landfill disposal after removing metals step (scenario 2) is the most adopted across Europe (Eurostat 2009).

Scenarios 4 and 5 were considered as case studies for post-shredder technology (PST) management strategies via processes which recover both material and energy. Anyway, neither of them is currently working in Italy, so it was necessary to gather data from scientific literature. Such reference processes were the Argonne National Laboratory Process (ANL, 2004) for "advanced material recovery and incineration" scenario and the Thermoselect (Thermoselect SA, 2010) process for "feedstock recycling".

LCA methodology was chosen because of its integrated approach, which allows to appropriately manage the flow of data and information which is linked to a productive system and regulated by the recent EU Directive 2008/98/CE, which states that a waste management system can differ from the traditional waste management hierarchy if it is supported by an LCA analysis.

The norms ISO 14040 and 14044 define four phases which an LCA analysis must conceptually follow: *Goal and scope definition*; *Life Cycle Inventory*; *Life Cycle Impact Assessment*; and *Interpretation*. The software used for the analysis was SimaPro 7.1.8. Data acquisition on materials and energy flow that were not obtained directly from primary sources was carried out with the database Ecoinvent.

Material and energy flows, inputs and environmental emissions were inventoried for each scenario. The main details and information are reported below.

Apart from scenario 1 that models the whole ASR landfilling (which is still carried out whenever any further recovering treatment from waste is not adopted by industrial plants), all other end-of-life modeled scenarios consider the recovery of nonferrous metals fractions, made by scenario 2 and amounting to 60 kg of metals, as a basis.

End-of-Life scenarios	*Material recovery*	*Energy recovery*	*Processing related emissions*	*Landfilling with transportation*
Landfilling				1000 kg of ASR, 150 km by truck
Advanced metals recovery	60 kg of metals		9 MJ grid electricity	940 kg of ASR, 150 km by truck
Thermal treatment with energy recovery	60 kg of metals	966 MJ grid electricity, 1263 MJ thermal energy	97 MJ grid electricity, 126.3 MJ thermal energy	226 kg of inertized residuals, 150 km by truck
Advanced material recovery and incineration	60 kg of metals, 237 kg of plastics	723 MJ grid electricity, 945 MJ thermal energy	981 MJ grid electricity, 94 MJ thermal energy, 700 MJ natural gas, 400 kg water; 1 MJ/kg $_{PUF}$ grid electricity, 3 MJ/kg $_{PUF}$ natural gas	169 kg of inert residuals, 5 km by truck
Feedstock recycling	90 kg of metals, 148 kg of chemicals (methanol), 27 kg of hydrogen gas	2566 MJ grid electricity	422 MJ grid electricity, 515 kg oxygen, 350 kg cooling water	230 kg of inertized residuals, 5 km by truck

Figure 46 - Main inputs and outputs considered for each scenario

Scenario 1: Landfilling

Modelling waste disposal in landfill involves many critical aspects due to the difficulty to establish unambiguous relationships among waste materials and their environmental impacts. Because of the lack of information available about the fate of wastes after they are disposed of, for each waste type material, embodied into the functional unit, some specific inventory processes were associated, with high degree of detail for leachate outputs and emissions, reported into the Ecoinvent Database (2008).

In accordance with ASR composition, it was assumed that a negligible contribution derives to biogas production from this kind of waste, even if some reactions of polymeric degradations may take place (Hunt 1995). Finally, transport processes were inventoried on an average distance of 150 km from shredding plant to landfill .

Scenario 2: Further metals recovery

The ASR end-of-life scenario 2 consists in a sequence of operating steps dedicated to non- ferrous metals recovery, modelling the current Italian management strategy: most shredders use to carry out a further recovery of non ferrous metals in the non ferromagnetic fraction (Santini et al. 2010, III; AIRA, 2007).

In order to create the second scenario for LCA analysis, an inventory of input/output flows was compiled, based on measures from the Fiori Group's Italferro plant.

Italferro plant, located in Santa Palomba (Rome), carries out the recovery of aluminium, copper, brass, steel and residual ferrous scraps by means of Eddy Current Machineries combined with an innovative Induction Sorting System process. Electricity requirements amount to 9 MJ/t.

Considering the composition of the functional unit used in this study, scenario 2 allows a separation of 60 kg of those metals from 1 t of ASR; the remaining fraction, amounting to 940 kg, will be disposed in landfill according to the assumptions of scenario 1. Other needs for auxiliary processes, such as transport to landfill (150 km) and infrastructure facilities were also included.

The following scenarios, namely scenario 3, 4 and 5, consider scenario 2 such as the starting point of ASR management. Thus, 60 kg of non ferrous metals are by default recovered by all of them.

Scenario 3: Thermal treatment with energy recovery

ASR incineration treatment is the second most adopted ASR end-of-life management system in Europe after landfilling (Eurostat 2009). However, European Countries carry out a thermal treatment of ASR waste only in co-combustion with MSW mainly due to the composition of the former, that presents some physical and chemical parameters resulting in difficult problems (for example, high heating value from plastic matter or significant presence of inerts) as well as many sources of pollution such as PVC or residual oils.

Usually, ASR/MSW co-combustion rates in European Countries range from 3% to 11% (Eurostat 2009). In this study, a North Italian medium sized (Frullo Energia Ambiente s.r.l., Bologna, Northern Italy) incineration plant was chosen as a reference for data inventory phase: in this plant a co-combustion rate of 5% ASR is performed and no changes in inputs and outputs (emissions) are observed at this rate.

As well as for scenario 2, even this one deals with the ASR input after treatments to collect 60 kg of such non ferrous metals. Incinerating the remaining amount of 940 kg, a recovery of 966 MJ of electrical energy and 1263 MJ of thermal energy, partially used for internal energy supply (about 10%). Residuals and fly ash amount to 21% and 3% of whole input, respectively; they are disposed by landfilling after inertization treatments. Waste transport in landfill (150 km) and facility data were also included into inventory.

Scenario 4: Advanced material recovery and incineration

The last two scenarios model PSTs as advanced waste treatments for ASR.

Reference for scenario 4 was the ANL Process, developed by Argonne National Laboratory. This treatment consists in two operating steps: i) a mechanical material separation performed to gather polymeric fractions altogether, from ASR, followed by ii) an intensive separation of each collected polymeric types by means of froth flotation (ANL 2008; Jody and Daniels 2006; Nourreddine 2007; Boughton and Horvath 2006).

In this scenario, 237 kg of single polymers (PUF, PP, PVC, PE, PP and ABS) were separated from the input of 940 kg against high inputs of energy consumptions: 981 MJ/t ASR of electrical energy (900 MJ for the froth flotation separating process, 72 MJ for waste incineration and 9 MJ from scenario 2), while thermal energy needs amount to 94 MJ. Natural gas and fresh water consumptions account for 700 MJ/t ASR and 400 kg/t ASR respectively. Recoveries of 723 MJ of electrical energy and 945 MJ of thermal energy are then achieved by scenario 4.

Furthermore, polyurethanes foams separated by ANL Process are treated using a specific washing process in order to prepare this material for market. Consumptions include inputs of washing agents (1%), grid electricity (1 MJ/kg PUF) and natural gas (3 MJ/kg PUF).

Since scenario 4 models a PST which does not exist currently in Italy, an *in situ* construction was assumed: i.e. this recovery facility was set on a distance of 5 km from the Italferro shredding plant in order to minimize environmental impacts relating to transport processes.

Scenario 5: Feedstock recycling

Even in this case, ASR treatment was modelled after the recovery obtained by scenario 2; it consists in a feedstock recycling, namely: i) a gasification process for syngas production, followed by ii) syngas conversion to methanol and other short-chain alcohols.

An inventory of flows was carried out by referring to the Thermoselect Process SA, that currently operates in Germany. This waste treatment claims inputs of ASR:MSW in the rate 45:55. According to (Drost et al. 2004; Hau et al 2008; Kaiser and Shimizu 2004; Ray and Thorpe 2007; Zhang et al. 2001) material inputs for oxygen (515 kg), zinc (3 kg), NaCl (10 kg) sulphur (2 kg) and cooling water (350 kg) were included into inventory. Scenario 5 produces 890 kg of syngas in addition to 2566 MJ of electrical energy recovery, 27 kg of hydrogen gas and 30 kg of metals, to be added to the 60 kg separated by scenario 2. The recovered 370 kg of CO from syngas and hydrogen gas were then converted to 148 kg of methanol and chemicals. Electricity consumptions amount to 422 MJ, with 9 MJ resulting from scenario 2.

According to a sustainable development, even for this scenario the place of a gasification plant was assumed to be chosen near the shredding plant, modelling the landfill disposal of residuals and fly ash (230 kg) on a distance of 5 km.

Life Cycle Impact Assessment

Impacts resulting from environmental loads of each scenario were quantified. According to ISO 14040 and 14044, ecoindicator'99 method by PRé Consultant B.V. (2001) has been adopted to characterise and quantify the main impacts in terms of potential effects on the following nine environmental categories: global warming, carcinogens, respiratory diseases from organic and inorganic substances, acidification and eutrophication effects, ecotoxicity, land use, mineral and fossil fuels depletion. According to this method, results were then worked out by adding them into three damage end points at a higher grade of understanding that refer to Human Health, Ecosystem Quality and Resources Depletion. Units of measurement used in this study were disability adjusted life years for Human Health end point, potentially disappeared fraction of plant species (PDF*m2*yr) and MJ surplus energy referred to ecosystem quality and resources depletion, respectively.

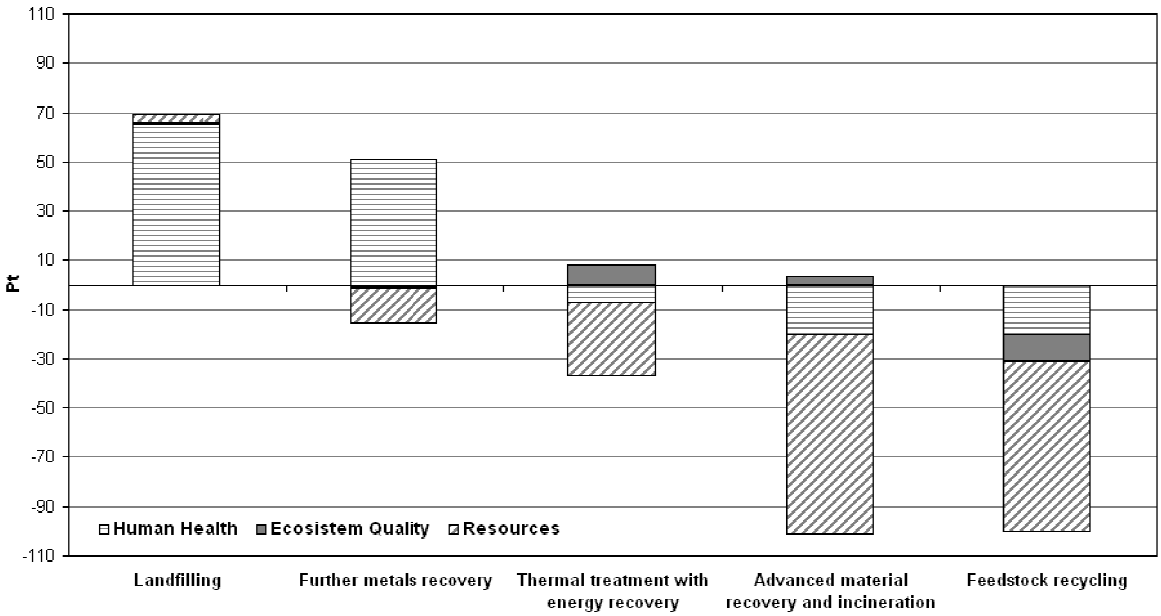


Figure 47- Life cycle impact assessment (source: Ciacci et al., 2010)

LCIA results show that:

i) the disposal of ASR in landfill is the worst scenario due to the direct impacts resulting from the disposal of polluted and hazardous waste as such ASR commonly appears, without any treatment aimed at energy or material recovery; thus, it results in a net loss of material.

ii) Recovering non ferrous metals fraction may reduce environmental loads, especially for resources consumption;

iii) ASR co-combustion in incinerator would allow a decrease in damages related to plastics landfilling, and further benefits resulting from energy recovery processes, reducing waste volume and destroying organic pollutants. In spite of the advantage resulting from the opportunity to operate in co-combustion with MSW (at the rate of 5% any significant variations in outputs were not observed), ASR incineration should not be considered as a long term alternative to landfill, since this end-of-life strategy do not allow the achievement of 85% recyclability target fixed by European Community.

iv) In terms of environmental impact, better results characterise post-shredder technologies modelled by scenario 4 and 5, with a little preference for “Feedstock recycling”. It is interesting to compare results even on the recyclability and recoverability rates gained by those scenarios: both allow the attainment of European targets, but scenario 4 reaches a higher recyclability score than the other one, leading to ask which strategy should be considered the best solution. Hence, identifying the best way to treat ASR waste may be quite difficult even as a consequence of the frequent variations that occur in ASR composition.

Of course in this study it was not possible to consider the whole range of technologies available at the present time, and the existence of other processes leading to further environmental improvement cannot be excluded. However, despite uncertainties and assumptions that commonly affect LCA studies, a comparison was performed among the most common management methods focusing on recyclability and recoverability rates, together with an assessment about environmental effects.

The results of this work show that recoverability and recyclability targets may be achieved only by treating ASR in order to separate high value added materials such as plastics and metals.

Finally, aiming at higher environmental benefits, post shredder technologies and end-of-life treatments should be integrated into eco-design strategies in order to produce new vehicles by processes with lower environmental impacts and leading to a reduction of waste generated from ELVs management chain.

Recommendations

The driving force of PSTs development is ELVs Directive targets achievement beside economic profit. Figure 48 shows recyclability and recoverability rates resulting for each scenario according to the ISO 22628 calculating procedures.

For a better understanding, 80.8% recyclability rate was assumed such as the starting point to calculate recoverability percentages for each end-of-life scenario. That rate refers to the Italian average issue resulting from those material recovery steps that commonly take place during drainage, dismantling and shredding phases (Santini et al., 2010).

End-of-Life scenario	*Recyclability (%)*	*Recoverability (%)*
Landfilling	80.8	80.8
Advanced metals recovery	82.0	82.0
Thermal treatment with energy recovery	82.0	96.3
Advanced material recovery and incineration	86.9	97.6
Feedstock recycling	85.6	96.2
ELV Directive targets in 2015	*85.0*	*95.0*

Figure 48- Achievable recycling rate for each created scenario

As shown in Figure 48, it is possible to notice that scenarios 1, 2 and 3 do not allow Member States to reach ELV Directive targets in 2015. This is in line with several studies and European Commission reports (GHK/BioIS 2006; Ferrão et al. 2006; Santini et al. 2010). On the other hand, PSTs ensure target achievement even though cost efficiency of these innovative technologies is still an open issue, since the number of industrial scale operating plants in Europe (and around the world) is still reduced.

Finally, ASR treatment appears unavoidable in order to reach those targets. In particular, fines separation followed by complete metal recovery and a plastic enrichment process whose residues can be thermally recovered allow to both reach targets and to reduce environmental impacts. Moreover, this scenario exploit existing facilities, shredding plants and incinerators, and it may entail less investments and treatment costs (per ton). Of course, as such ASR incineration is not fulfilling recycling requirements thus, intensive metal separation has been studied, and results are reported in the next chapters.

Auto shredder residue LCA: implications of ASR composition evolution

Since 1990s, remarkable variations have been observed in new vehicles production, basically due to the increasing use of light materials, such as polymers and non ferrous metals – mainly aluminium. This due to the fact that 80% of CO_2 emissions are produced during the use phase combined with the fact that one third of the vehicle consumption depends on its weight. Such trend answers the need for more sustainability faced by the automotive sector, which is claimed to drastically reduce CO_2 emission during the usage phase: from 1995 CO_2 emission levels decrease from 161 g/km to 120 g/km.

The goal of lightweight is to meet the requirements of an Extended Product Responsibility (EPR) by using the scope for decision-making during the product development to realize a maximum product benefit for costumers and producers during the life cycle and to minimize its economic, ecologic and social cost risks. This leads to some considerations:

(1) design determines costs, while all other phases are mainly those which cause the costs;

(2) whether the costs increase or mainly lie in production or use depends on the product;

(3) changes in the design affect costs throughout the life cycle;

(4) the higher environmental costs are caused at the disposal step.

This is an important consideration that should trigger the designers' attention on Design for Recycling (DfR) and Design for Disassembly (DfD) technique applications (Santini et al., 2010).

This chapter reports a study carried out by the candidate and published as Passarini et al, VI, in which the candidate dealt with an application of LCA analysis to assess environmental rebounds from the composition evolution of Automotive Shredder Residue. First step towards sustainability occurs since new vehicle production, in accordance with the Directive 2008/98/EC that claims prevention as primary option for waste reduction.

Design for Environment practices, including Design for Recycling, Design for Disassembly, and Ecodesign, are some of the management tools that may support a new vehicle production environmentally-oriented. These are in line with Life Cycle Thinking concepts, that remind every stage or phase in a life cycle product determine burdens on the environment and that a better performance can be achieved only through a comprehensive approach.

With this intent, the research focused on environmental consequences resulting from the increasing use of light materials in cars, especially during the End-of-Life stage when a vehicle is treated for material and energy recovery before the final disposal. Indeed, despite of increasing use of plastics and non-ferrous metals help to counterbalance CO_2 emission during car usage, they affect collection activities for recovery and recycling. While iron and steel parts are technically and economically feasible to recovery, plastics and aluminium are instead affected by higher economic costs and technical obstacles due to physical and chemical limitations.

In this study three potential evolution scenarios of waste composition were considered with respect to the functional unit of 1 ton ASR. These ASR material mixes were then investigated by performing a comparison among different waste management scenarios. Waste treatments have been modeled in a previous paper (Ciacci et al. 2010) and consist of (1) ASR landfilling after non-ferrous metals removal, (2) ASR-MSW (95%-

5%) incinerating for energy recovery, (3) non ferrous metals recovery followed by froth flotation for plastic collection and energy recovery of the remaining waste, and (4) chemical recycling coupled with energy recovery by a gasification process. Last two scenarios modeled are Post Shredder Technologies (PSTs) and were referred to operating processes by the Argonne National Laboratory (ANL) and the Thermoselect.

ASR material mixes were compiled according to (a) the current ASR material breakdown "Baseline", (b) ASR composition expected by 2015 (GHK/Biois 2006) with an increase in plastics and non-ferrous metals, and (c) ASR resulting from application of Ecodesign principles in new vehicle production and aiming at decreasing the number of plastic types for a quantitative and efficient recovery "2020".

Analysis was performed by SimaPro 7.1 software and the database Ecoinvent 2.0. Life cycle inventory were carried on a data collection from operating plants, literature case studies, company reports and expert elicitations.

Life cycle impact assessment was based on the Ecoindicator99 method, according to endpoint-oriented approach. Damage categories considered measure impacts for the human health, ecosystem quality and resource consumptions.

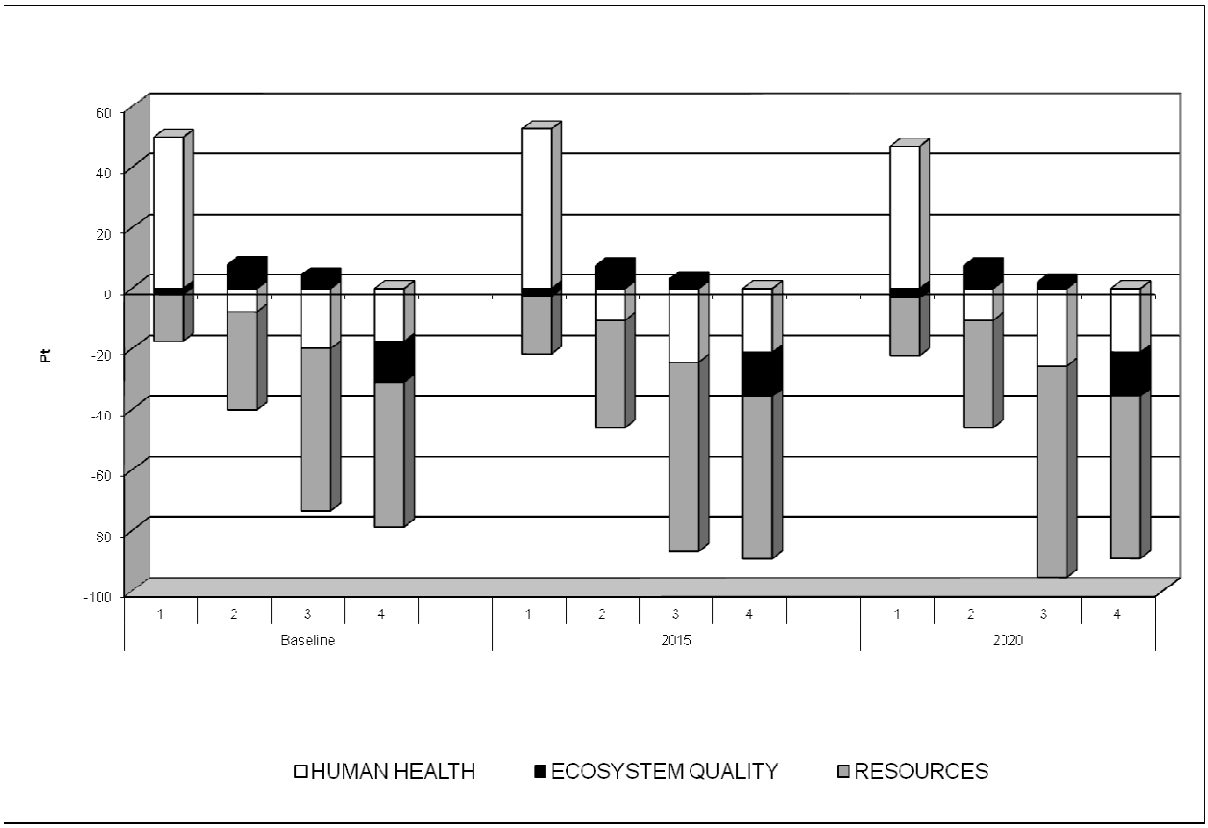


Figure 49 - LCA results (source: Passarini et al., 2012)

Overall, the results show the best environmental performances for PST waste management scenarios, confirming the outcomes of the previous study (Ciacci et al. 2010). However, operation conditions, changes in input waste or even local and geographical features may affect the general overview. Chemical recycling scenario seems to achieve a best score in terms of ecosystem quality as scenario 3 and 2 pay for incinerating emissions.

Looking at the temporal trend, environmental impacts from missed material separation for recycling increase for landfilling and co-incineration scenarios. On the other hand, plastic and non-ferrous metals, particularly for aluminium, collection enhance benefits for scenarios 3 and 4.

Differences between PSTs scenarios are small and they may be overturned depending on marginal conditions. However, the ASR material mix compiled according to Ecodesign principles shows scenario 3 more dependent on environmentally oriented design in new vehicle production than the chemical recycling one. In this sense, whether design for environment practices will take place mechanical recycling followed by energy recovery of the remaining waste might be seen as preference in ASR waste management strategies from resource conservation point of view.

Reducing material types and increasing the use of energy intensity metals (aluminium) for recovery and recycling purpose would lead to better performances for mechanical and chemical recycling options. However, waste-to-energy plants might be exploited in a close-loop approach whether part of energy recovered supplied hybrid and full electric vehicles.

Decision makers should include economical evaluation and technical analyses taking into account the turnover for recycling processes and spreading of markets for secondary products.

Eventually, the study investigates potential benefits from aluminium and PP-PE recycling activities within the Italy country boundaries.

European Community claims for Italy to achieve a reduction in CO_2 emissions at 13% and to increase renewable energy production at 17% (Directive 2009/28/EC).

Considering theoretical amounts for aluminium and PP-PE recoverable from ASR, Italy might of huge benefits from recycling activities for these materials.

Estimating about 2800 kt of aluminium and 585 kt of PP-PE the amounts resulting from ASR separation plants by 2015 whether Ecodesign approach will take place, estimates in terms of avoided impacts for Global Warming Potential (GWP) and non-renewable energy consumption indicators result for about 4.0 E+08 and 1.6 E+10 MJ respectively.

Finally, the study conducted underlines the need to include life cycle thinking practices into waste management for supporting decision making for future challenge in the automotive sector.

Recommendations

Considering the previous acknowledgements, while waiting for innovative eco-designed ELVs, it would be very important if car producers would design new vehicles with a certain percentage of material obtained from recycled ASR. For instance, a type-approval requiring that a new vehicle would have at least 10% of plastics deriving from ELVs non-metallic fraction by law, will lead to many advantages:

- creation of a real market for recycled materials;
- improved dismantling and recyclability rate because of the increased market price of recycled materials, now almost valueless;
- once having a market for its “products”, shredder plants may evolve in facilities dedicated to ELVs treatment and so forth ensure a more constant composition of shredder residue over the time;
- DfD and DfR would be strongly encouraged and, more important, also economically boosted, for the necessity of producing a certain amount of recycled material to build new vehicles.

Finally, as far as the responsibility for properly managing waste is not extended to the producers, designers will not have any economical constraint to pursue eco-innovation solutions, since the waste continues to be pre-treated and dismantled by other actors taking part to ELV treatment chain.

POST SHREDDER TECHNOLOGIES (PSTs)

From previous chapters it results that, even by means of correct and efficient de-pollution and dismantling operations, ASR is generated at the shredding step. Standard metal recovery technologies are not 100% efficient, in fact, ASR still contains up to 10% residual metals like iron, steel, copper cables, aluminium, etc. (Morselli et al, III; Vermeulen et al., 2011; Noureddine, 2007; Dalmijn & De Jong, 2007). Across the world, ASR production is rather different, as different are the priorities driving its disposal schemes, treatment plants and regulations.

In Europe light fluff air suction is a well established practice that brings to heavy fluff separation treatment, usually by means of dedicated mechanical separation or floatation plants. Light fluff is not yet intensively treated for the recovery of valuable metals, except for a small quota of operators. Landfill prices are ever growing especially in the northern countries as an incentive to reach the EU ELVs recycling and recovery targets. Denmark, for instance, has implemented a two-phase plan for taxing landfilled shredder residue. As of January 1st , 2012 a tax of DKK 160 per tonne of landfilled shredder residue will be applied, and as of January 1st , 2015 the tax will reach DKK 475 per ton. Due to this tax plan, which is going to be applied to all European MS in the future, there are incentives to find alternative processing methods instead of landfilling shredder residue (Moakley et al., 2010).

In the US the situation is quite opposite, with landfill prices that can be one order of magnitude less than European ones. Moreover, air suction is not applied extensively thus, in general, US ASR contains more metal than the European one. Energy recovery is not yet considered in the US due to the lower energy price which brings waste incineration to be not competitive with standard power generation. In addition, wide distances between cities, ELVs recycling plants and ASR landfills have not risen an “environmental concern” yet. ASR improved recycling is, so far, expected to depend only on its own profitability, and not on policy compliance. In any case, ASR landfills mining is not excluded in the years to come.

Japan is the third vehicle and ELVs producer in the world. In this Country, auto makers and importers are required to collect and recycle ASR into reusable materials or to perform thermal recovery at authorized facilities (in Japan there is no more space left for landfills). Many of these facilities are equipped with gasification melting furnaces. Both the metals and combustibles materials recovered from the shredder residue are often directly sent to non-ferrous metals smelting plants (i.e. incineration of ASR using copper smelter infrastructure) (Togawa, 2008).

Back to Europe, a great technological innovation is expected in the forthcoming years due to the approaching 85% recycling rate threshold (Santini et al., V). PSTs are processes designed for recovering material or energy from ASR. In summary, there are two main categories of technology, those based on *mechanical sorting* of the waste into different fractions that can be recycled and sold; and those based on *thermal treatment* of the waste stream to generate feedstock for energy generation (GHK/BioIS, 2006, Annex 3).

In the case of mechanical separation, the main products are metals (which usually sustain the economy of the whole process), plastic granulates (for recycling in plastic products or energy recovery), shredder fibres (to be used in sewage treatment, or energy recovery) and sand (to be used in construction, landfill cover or disposal). Current technology still generates waste that requires disposal in incinerators or landfill sites.

Mechanical based ASR recycling technologies

In this chapter, a review of PST equipments is carried out. Innovative metal sorting technologies are described as ASR pre-treatment aimed at energy recovery despite the fact they have their own economic sustainability in metal recovery itself. The following equipments were developed by SGM-Gantry SpA, which holds all the patents and intellectual rights. During the third year of this PhD, an active cooperation between the candidate, Gruppo Fiori and SGM-Gantry SpA, especially represented by Mr. Danilo Molteni, laid the basis for the correct comprehension of separation principles and the efficient exploitation of separation machineries.

Innovative metal sorting technologies

When aiming at metal recovery from ASR, it is imperative to work on well-defined size categories.

First step in ASR treatment is sieving. In order to optimize metal separation, the following fractions are created:

- → Fine fraction (0-20 mm)
- → Regular fraction (20-50 and 50-80mm)
- → Oversize (>80mm)

Figure 50 - Rotating drum (picture taken by the candidate at ACIPCO plant, Alabama, US)

Each fraction is treated by means of a dedicated line. The logic cascade of sorting equipments do not vary with size and it involves:

1. Magnetic material removal
2. Non-ferrous metals removal
3. Residual metals removal (non magnetic stainless steel and insulated copper wires, ICW)

Fine fraction is treated by a cascade of the following machineries: vibrating table, Dynamic SRP and Eddy Current Separator (VIS and SIS).

Figure 51- SGM fine line prototype (source: courtesy of SGM-Gantry SpA, 2012)

At first, a vibrating table opens the material to treat. This is a very important operation since dynamic magnetism effect depends on the distance between the source and the target metal particle, thus if the material is well-distributed on the conveyor belt of the following machine, its efficiency is likely to be higher (it is key to prevent ASR heaps on the conveyor belt).

Then, Dynamic-SRP allows to separate ferrous metals thanks to a patented magnetic system: a floating pulley, which revolves more slowly than the main belt speed, see Figure 52.

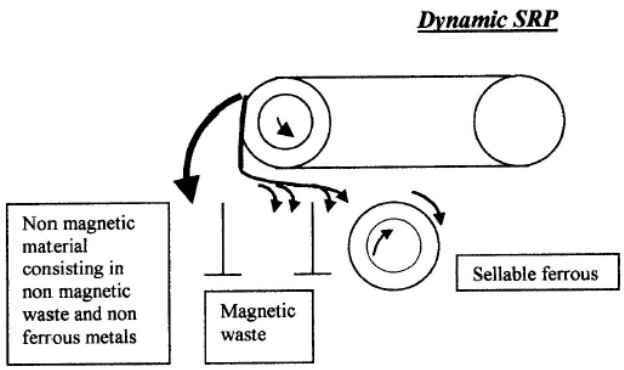


Figure 52 - D-SRP flowsheet (source: courtesy of SGM-Gantry SpA, 2012)

It is advisable to position Dynamic-SRP before ECS because it allows to both get back the valuable ferrous material from the magnetic waste and to improve non-ferrous metals recovery by the ECS (avoiding interactions between ECS changing magnetic field and ferrous materials and protecting ECS against ferrous damage exposure).

Dynamic SRP allows to separate the material into three different flows: valuable ferrous, magnetic waste, non-magnetic fraction (destined to ECS).

Figure 53 - valuable ferrous material, magnetic waste, non-magnetic fraction (source: courtesy of SGM-Gantry SpA, 2012)

After ferrous material separation, the remaining fraction is treated by VIS: a high frequency eddy current separator located in line which recovers non-ferrous metals down to 1 mm size. In short, eddy currents (also called Foucault currents) are electric currents induced in conductors when a conductor is exposed to a changing magnetic field (both due to relative motion of the field source and conductor, as in this case, or due to variations of the field in time). This can cause a circulating flow of electrons, or current, within the body of the conductor. These circulating eddies of current have inductance and thus induce magnetic fields which can cause repulsive effects (among others).

The stronger the applied magnetic field, or the greater the electrical conductivity of the conductor, or the faster the field changes, then the greater the currents that are developed and the greater the fields produced[4]. As a result, thinner, slotted and laminated materials make the currents difficult to circulate, so far hindering ECS sorting. Another factor influencing eddy current strength is the density of the element or alloy to sort: the heavier the element, the stronger the power needed. In fact, lead, bronze and other heavy metals are much more difficult to divide than aluminium. It is possible to notice this effect by passing again the ECS waste material: with a second passage it is possible to recover a further 2%$_{wt}$ approximately of non-ferrous materials, in particular small, wire-shaped heavy metals.

Figure 54 - Fine fraction non-Fe metals first passage on the left and second passage on the right

[4] $P = \frac{\pi^2 B_p^2 d^2 f^2}{6k\rho D}$ *where:*

k, is 1 for thin sheets, 2 for thin wires
P, power dissipation (W/kg)
B_p, peak flux density (T)
d, thickness of the sheet or diameter of the wire (m)
f, frequency (Hz)
ρ, resistivity (Ωm)
D, specific density (kg/m^3)

The difference between the first passage product and the second passage is evident and it is mainly due to the effect that tend to convoy eddy currents into larger, flat pieces than into smaller ones. This leads to the fact that lost metals are in prevalence small and heavy and that a correct sieving is the key for an efficient separation. The shape itself plays an important role: spherical shape materials or wires hinder the formation of eddy currents (i.e. capillary cables were born exactly to prevent power dissipation, such as eddy currents).

The induction drum of SGM-Gantry VIS and SIS ECS models is CONCENTRIC (see Figure 55) and it has a direct drive rotor in order to get to the maximum frequency (from 3000 to 4000 rpm). Differing from competitors ex-centric induction drum, the non-ferrous material gets lifted by the magnetic field *on top* of the rotor, causing a net 45° upward lift separation between metals and residual materials. If the non-Fe material was lifted when gravity began to accelerate it with the residue, as in the ex-centric system, the final effect would be much more similar to a ballistic effect than a real vertical launch, causing more dirt and undesirable material to enter in the final product.

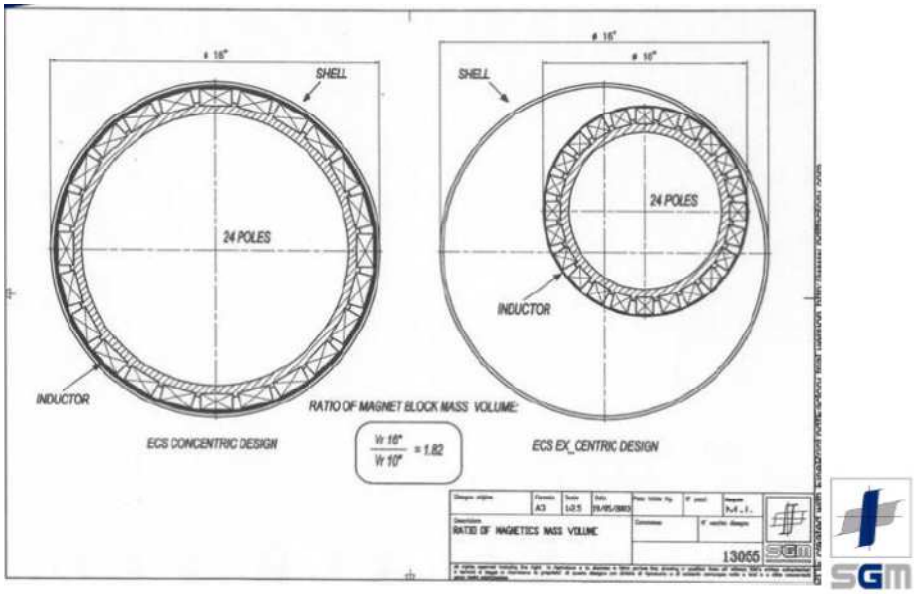


Figure 55 – SGM VIS/SIS concentric induction drum on the left and ex-centric induction drum on the right (source: courtesy of SGM-Gantry SpA, 2012)

Another difference is the magnetic frequency of the SGM eddy current with respect to the ECSs developed by competitors. "Magnetic frequency" means the number of complete cycles (North – South – North) per second, given by the number of rows of magnetic poles inside the induction drum (a) and by the speed of the same induction drum (b).

One among the principles of magnetism states: "*the smaller the size of the metal piece to be recovered, the higher the magnetic frequency needed*".

Therefore, to improve separation effect, the combination of the two elements (*a,b*) of the magnetic frequency principle claims for:

a) higher quantity of magnetic blocks inside the concentric induction drum (each one giving a N-S-N cycle),

b) higher rotation speed (rpm/min),

which, united in the induction drum of the SGM VIS machinery, lead to an overall higher magnetic frequency that shows improved and cleaner recovery of non-Fe metals.

A SIS eddy current separator (the ECS used for the regular size fraction: 30-120mm) works at 3.000 rounds per minute which means, considering 24 rows of magnetic pole shoes: (24 x 3.000rpm) = 72.000 / 60 seconds = 1.200 / 2 = 600 complete cycles N-S-N per second. A VIS eddy current separator used for the fine fraction works at 4.000 rounds per minute which means, considering 24 rows of magnetic pole shoes : (24 x 4.000rpm) = 96.000 / 60 seconds = 1.600 / 2 = 800 complete cycles per second.

Standard ECSs work at a much lower speed, which results in a lower magnetic frequency, causing losses of metals to recover, especially those with smaller size (and those with non-flat shapes like copper wires, bronze bearings and aluminium radiators), and also more contamination of the product.

Typically, the content of metals still present in the waste of ECS working on ASR coming from shredders with or without suction vary from 3 to 8%. These metals get lost after being processed by ECS because they weakly react to Focault currents (stainless steel, copper wires, non-ferrous metals locked with ferrous pieces) or because they simply enter within the error margin of the ECS. The equipment next in line to extract the residual metals is Air Sensor: a separator with inductive proximity sensors, whose working scheme is reported in Figure 56.

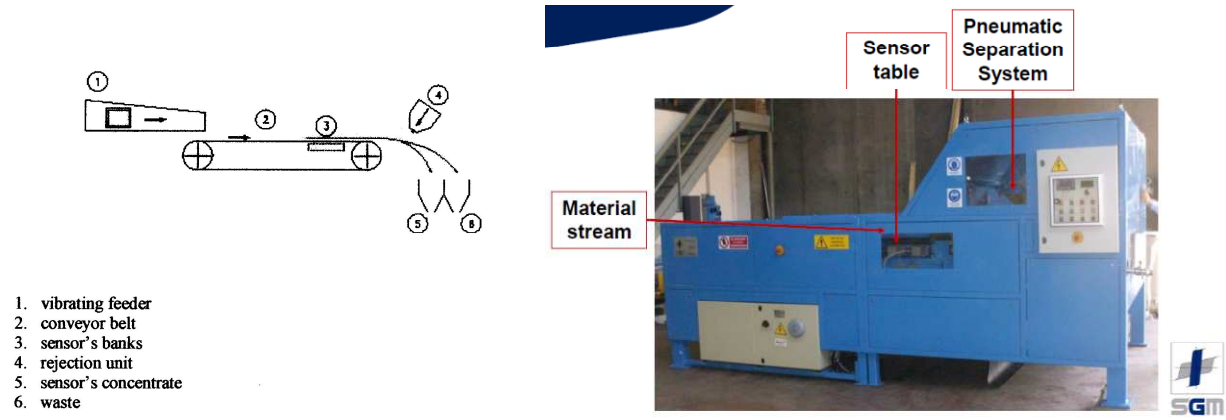


Figure 56 - EMS and EMSF working scheme (source: courtesy of SGM-Gantry SpA, 2012)

The Air Sensor works with inductive proximity sensors to identify the material to process. The inductive proximity sensors are based on the principle of reluctance variation which is particular to electromagnets, when a ferromagnetic object is in its proximity: the presence of ferromagnetic material within a magnetic field allows the field to close more easily, with a consequent reduction of reluctance. The internal circuits of the sensor note a reluctance variation and change the exit signal, once a certain level has been exceeded. Thus, these proximities can only sense the presence of ferromagnetic objects; moreover the reading distance is usually quite low (a few millimetres). These sensors can increase up to very high frequency levels, around thousand times per second, so that they can note the presence of fast moving objects. The inductive proximity sensors communicate with microprocessor electronic cards (SPLAT CARDS), which work out signals and drive the pneumatic separation system.

Air Sensor machines function in two different ways: with a pneumatic separation system which fires from above (EMS ..”-R) or from below (EMS ..”-C). The choice depends on the characteristics of the material to process: EMS..”-R is used to optimize metals recovery (concentration higher than 50%), whereas EMS..”-C is used to concentrate and clean the produced metals (concentration higher than 90%).

Beside high productivity and (*almost*) complete metal recovery from ASR, EMS dynamic sensor allows the user to adjust the sensitiveness of sensors in order to "blind" them to less inductive materials, such as insulated copper wires. This feature is very noteworthy in copper wires final recovery. Cables are usually fine shredded (around 3mm long) to liberate copper from the PVC wrapping and the resulting copper "needles" granulated into a turbine. Then, by means of a vibrating air table separator, copper granules are sorted from plastics. This process works fine with cables but if steel pieces enter among the shredder blades or into the granulator, the latter get broken and additional costs are charged to the plant management.

At the same time, stainless steel gets polluted by small quantities of copper (>0.3%$_{wt}$) , thus, it is better to leave these two materials separated and not to create an "*all metal*" product, namely Zurik[5].

By fine-tuning sensors and locating more EMSs in line, it is possible to sort out independently steel (by rising proximity sensors reading distance) and then copper wires. Hand pickers are required to refine the final product but their task is not like an intensive positive product recovery, but rather an undesired material removal from the product flow.

Figure 57 - copper wires and stainless steel products (source: courtesy of SGM-Gantry SpA, 2012)

The residual material is now metals free and, especially for regular and oversize fractions, free of inert such as glass and stones. Its composition makes it particularly attractive for energy recovery, an issue that is described in detail in the next chapter. Figure 58 reports a sample of the heavy ASR pilot line negative. This

[5] Zurik: SHREDDED NONFERROUS SENSOR SORTED SCRAP (predominantly stainless steel).
Shall be made up of a combination of the nonferrous metals: stainless steel, insulated copper wire, aluminum, copper, lead, magnesium, nickel, tin, and zinc, in elemental or alloyed (solid) form. The percentage of each metal within the nonferrous concentrate shall be subject to agreement between buyer and seller. Material generated by computer sensing equipment (e.g., induction sensor sorting or X-ray) technique(s). Shall have passed one or more magnets to reduce or eliminate free iron and/or large iron attachments. Shall be free of radioactive material, dross, or ash. Material to be bought/sold under this guideline shall be identified as "Zurik" with a number to follow indicating the estimated percentage nonferrous content of the material (e.g., "Zurik 90"means the material contains approximately 90%non ferrous metal content). May also be screened to permit description by specific size ranges (ISRI, 2011).

waste contains can be a suitable feeding material for any thermal treatment (included pyrolysis and Thermodynamic Cracking technology, both described more in detail in the homonym chapters) because it contains nearly no cables and more than 99% of polymers.

Figure 58 - Heavy ASR treatment line negative sample

Usually, despite ASR calorific value (13–25 MJ/kg), the high ash content, the elevated chlorine and heavy metal concentrations limited its use as fuel substitute, if used as such (Vermeulen et al., 2011). The new heavy ASR treatment line has been conceived to limit all these constraints and give a “negative” >30mm flow that could be suitable for thermal recovery.

Thermal based ASR recovery technologies

Once metals and fines[6] are removed, residual ASR is basically made of plastics, rubber, textile and other organic materials. Metals accounted for about 5%; thus, after intensive metal recovery, estimated ELV recycling rate is around 83%. Now, valuable plastics are the target.

ASR plastics recycling processes (Argonne, VW SiCon, Galloo Plastics, MBA Polymers, etc.) usually involve a physical plastic enrichment step and a second polymers separation step. Physical separation produces material concentrates from bulk shredder residue:

- → Foam
- → Ferrous and Non-ferrous Metals
- → Polymer Concentrate
- → Fines/sand
- → Residue (PVC containing)

Then, in order to divide plastics in single families, a wet process (floatation, froth floatation) is performed and usually polyolefin (PE,PP) are quite easily recovered at a first stage. Other polymers that can be recovered are: ABS, Nylon, PVC , HIPS. PST technologies developers claim for sorted polymers to have a purity of about 95% and confirmed the technical feasibility of recovering and reusing polyolefin from shredder residue. The main issue with polymers sorting and reuse is that molecules are subjected to a molecular weight downgrade, and thus properties downgrade, at each thermal step they go through (i.e. extrusion, moulding, etc.). Moreover, with regard to ASR polymers, they are as an average 10 years old plastics, containing flame retardants and other different fillers and during their life cycle suffered UV light and thermal cycle degradations. In fact, all the polymers recovered with these PST are often reused in black car hood component, since passenger compartment quality standard for new vehicle is generally too low.

Moreover, according to a recent report on plastic to fuel (PTF) technologies (4R, 2011), there are a number of reasons why many scrap plastics and resin products are not recovered and mechanically recycled. Technically speaking, a majority of waste plastics can be mechanically recycled, however the economics of doing so often do not favor the mechanical recycling, especially of contaminated plastics and/or multi-layer plastics. The condition of mixed plastics at end-of-life can make it economically unfeasible to mechanically recycle them, and in some cases, stable recovery markets for certain resins and products are lacking. However, since the latest generation of pyrolysis technologies are designed to accept a wide variety of resin types, they can accommodate many forms of contamination and require little pretreatment before being fed into the system, PTF technology could present a potential alternative to landfilling non-recycled plastics (4R, 2011).

So far, the author preferred to focus on plastic concentration followed by conversion to fuel or chemicals instead of plastic intensive sorting and mechanical recycling.

[6] size < 10mm. The finest fraction of ASR generally has the highest ash and mineral oil content, combined with the lowest calorific value (Vermeulen et al., 2011).

Italian ASR thermal recovery state of the art

At an industrial level, in Italy it is worth mentioning only some experiences that deal with the simultaneous treatment, in small quantities, of ASR with other types of waste, mainly inside plants devoted to the energy recovery of urban waste and non-dangerous special waste.

In this regard, it's surely important the experience carried out by HERA Company, at the energy recovery plants in Granarolo (Bologna) and Ferrara. Both these plants received the authorization to treat the non-dangerous special waste identified with the European Waste Catalogue (EWC) 19 10 04 code (fluff – light fraction and dust -, which is different from the ones with code 19 10 03).

In particular, at the plant in Granarolo, ASR from Gruppo Fiori was used. This plant has a treatment capacity of around 600 t/day of urban waste, and can continuously treat a share of ASR which ranges from 5 to 10% of the overall load, without facing any particular operative problem, nor negative results in the quality of stack air emissions.

As for the use of ASR as an alternative energy source (co-incineration) in industrial plants, no feedback has been given on the fact that such waste, and/or combustible fractions derived from more or less intensive pre-treatments, are currently used by the iron and steel industry or cement factories as a substitute of traditional fuels.

Two PSTs pilot scale plants are currently under development in Italy (De Stefanis, 2011):

1) Centro Sviluppo Materiali (CSM)

As a concept, the treatment is based on a serial combination of two systems composed of:

• a mechanical/*hydromechanical* pre-treatment system for the ASR designed by Centro Rottami Srl;

• a thermal treatment system developed by CSM for the combined recovery of matter and energy.

The input ASR undergoes a first selection (Centro Rottami Srl holds the patent of it) in order to have three flows made by: fine fraction, metals and heavy materials and plastics.

After the fine fraction (<10 mm) and plastics are shredded to a size which is inferior to 30 mm, they feed the following thermal treatment phase, which has been created and patented by CSM.

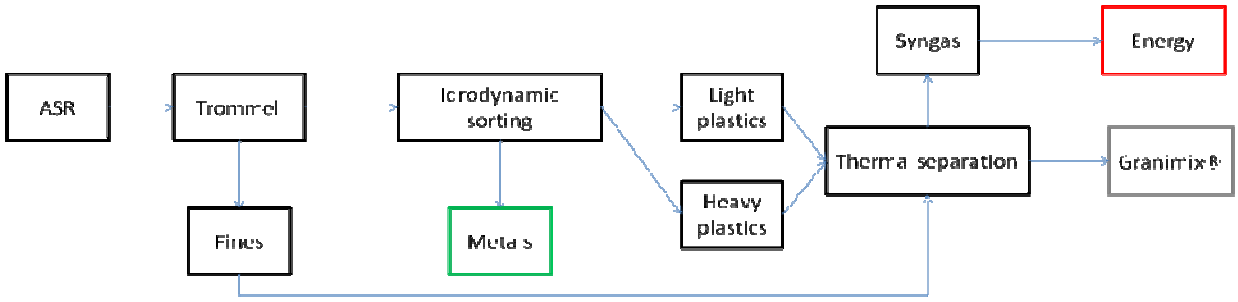


Figure 59 - Centro Rottami Srl and CSM plant layout

To summarize, the thermal treatment system displays these equipment:

• a rotating drum drier, at indirect heating in which enters the material to be treated;

• a rotating drum gasifier (reported in Figure 60).

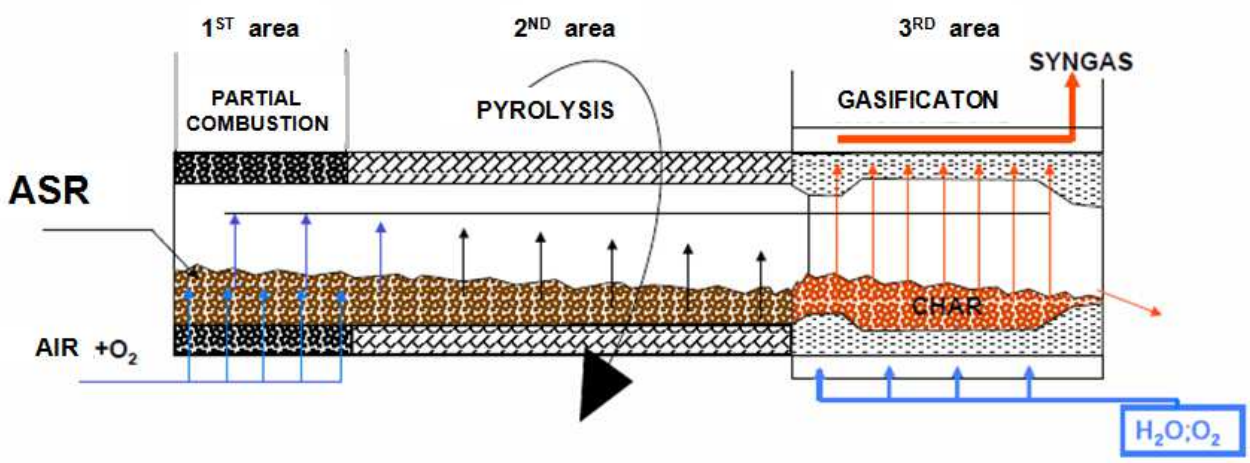


Figure 60 - CSM rotating drum gasifier

The air required for the process blows from the bottom. The partial combustion of the waste takes place in the first area of the drum, the central area hosts the pyrolisis while the final area realizes the gasification.

CSM developed this system in its laboratories, by means of building for each equipment a pilot unit with a capacity of around 100 kg/h (dryer) and around 150 kg/h (gasifier). Various trials have been performed on each equipment.

The recovered material is composed of:

• a material which is mainly formed by inerts (in addition to reduced percentages of residual carbon) named “Granimix” which can be used in the manufacturing of bitumen concrete, partially as a substitute of inerts for road construction;

• a syngas to be used in the production of energy.

The syngas is currently burnt into an oxidizer and the produced fumes, except for a reduced flow for the drying operations, are cooled down inside an heat exchanger and treated in an air cleaning system before their release into the atmosphere.

Based on this principle, a demonstrative plant is being started on an industrial scale at the Centro Rottami Srl plant in Cisterna (Latina), with a capacity of 2.5 t/h.

Future developments go towards the creation of an energy recovery system which uses electric energy production in a conventional cycle (in case the current display remains the same, which directly burns

syngas) or, the use of the very same one, properly treated, in high efficiency conversion cycles (internal combustion engine, gas turbine). The reported energy balance of this plant is 2.8 MWhe per 3.5 tons of car fluff <30mm, that is 0.8MWhe/ton (Salvati, 2009).

2) MAIND

In 2006, the Italian Ministry for Environment and Maind S.r.l. (Verona) signed an agreement protocol for the realization of a study oriented towards the evaluation of suitable technologies of combustion as final disposal technology ASR. This system shall have a capacity of about 100,000 t/y of waste. Two of this plants shall be placed in the Northern and Southern Italy areas for the treatment of about 200,000 t/y of ASR, that is about 85% of the total car fluff produced in Italy (De Stefanis et al., 2011).

The full-scale plant, designed for the thermo-valorization of tyres, was purpose-modified to allow 100% fluff combustion (Mancini et al., 2010). Several tests were carried out and lasted from about one hour to about 40 h of continuous fluff feeding. Experiments were carried out by alternatively substituting the tyres supply with fluff batches during the standard treatment practice of the plant.

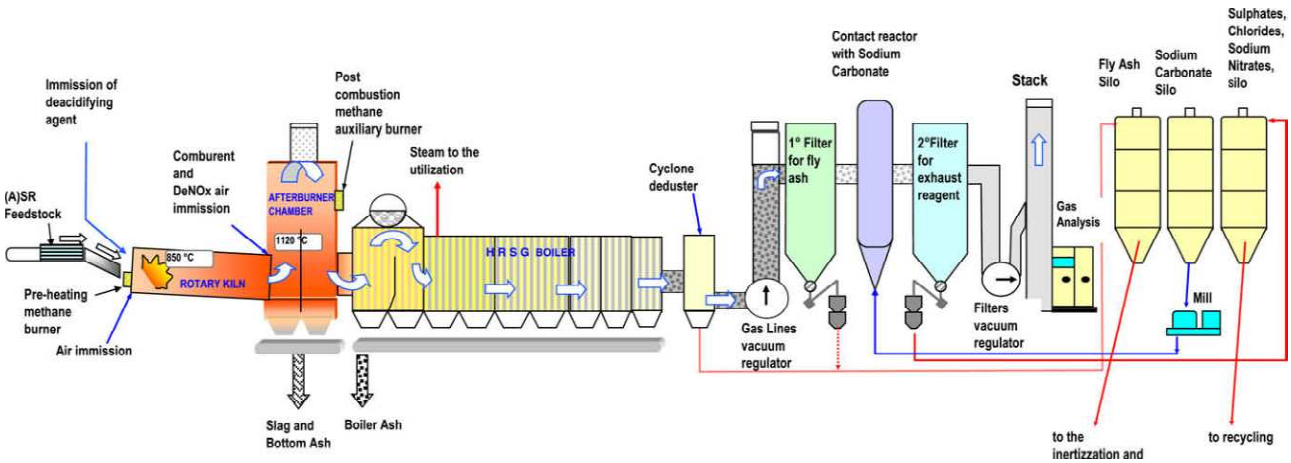


Figure 61 - Operational layout of the MAIND plant (source: Mancini et al., 2010; http://www.maindgroup.com/default.asp?pageID=3)

The plant consist of a rotary kiln with a pre-heating methane burner. The gases produced in this kiln get oxidized in afterburner chamber. The hot flue gases released from the afterburner chamber reach

the boiler where their energy content is used to generate steam at overpressure and it is used to drive a turbine in order to produce electricity. Flue gases are cleaned to such an extent to ensure reliable compliance with legal limits, assuring an adequate safety margin (Mancini et al., 2010).

Specifically, three ASR samples were created: 1) 70% ASR and 30% white goods SR and 3) 100% car fluff from the same shredding plant, while sample 2) 30% ASR and 70% waste-collection SR with higher fines content due to smaller grid size of the second shredding plant. Fluff hourly consumption had a typical value of about 2400 kg/h.

Results show the potential to achieve the generation of 0.9 MWh of power per ton of ASR burnt, despite the humidity and inert content (Mancini et al, 2010), but data from a most recent study report 0.75 MWh of power (De Stefanis et al., 2011). In fact, the ASR underwent no pre-treatments and this is maybe the reason why 0.61 energy efficiency parameter, calculated in accordance with the Directive 2008/98/EC, has been obtained during the tests (Mancini et al., 2010). Moreover, even though air emissions didn't exceeded law allowances, analysis of solid residues indicated that slag can be landfilled as an ultimate non-hazardous waste material while both fly and bottom ash are classified as hazardous wastes. Slag represents about 18% of initial ASR weight and ashes about 3%, that have to be properly treated before their final disposal in landfill.

Pre-treatment is fundamental in ASR thermal recovery since about 30 to 40% of its mass is non combustible. Moreover, pollutants such as hydrocarbons and heavy metals, tend to remain in the fine, inert fraction (Morselli et al., II). Sorting technologies reported in the previous chapter aim at both metals recovery and secondary solid fuel production because the only route allowing to reach 95% ELV recovery rate is an efficient combustion of the ASR. In fact, burning raw ASR in MSW incinerators cannot be a proper solution since this technology produces almost 20 to 25% of waste slag and ashes, mainly caused by non

combustibles inert, soil, glass and metals. Since ASR represents a rough 20% of an ELV mass, direct incineration is likely to cause more than 5% residues non allowing Italy to reach 2015 recovery target.

In the next paragraph some ASR pre-treatment operations are analyzed and laboratory scale pyrolysis experiments are reported.

Laboratory scale pyrolysis tests

Pyrolysis is the thermal cracking of long chain molecules in absence of oxygen. Particularly, when applied to plastics, pyrolysis brings C-C bonds to brake and basically to molecular weight reduction. Main pyrolysis products are a gaseous fraction, a liquid oil and a carbon residue so called "*char*". Usually cracking begins at 400°C and pyrolysis may occur up to 800°C. In general, 400°C pyrolysis produces alkenes and other linear, unsaturated products while rising temperature up to 800°C the share of aromatic compounds on the total products is predominant (Day et al, 1999).

As resulted from previous chapters, ASR contains up to 50% polymeric materials among rubbers, plastics and foam rubber that are suitable to pyrolysis treatment. It is our experience in the shredding and car recycling fields that the major constraints which have limited ASR pyrolysis industrial development up to now are:

- → (i) high chlorine levels in the ASR (coming from up to 3% PVC content in new vehicles),
- → (ii) heavy metals contamination (mainly Pb, Zn, Cu),
- → (iii) slag disposal, and
- → (iv) high pretreatment costs and sudden variations in the composition of the feed

(Morselli et al., 2010; Vermeulen et al., 2011; GHK/ BioIS, 2006).

(i) PVC combustion can release both hydrochloric acid (which can damage gas treatment equipment) and dioxins. (ii) Heavy metals, particularly the more volatile ones, concentrate in flue gas or in the finest particulate, requiring efficient, thus expensive, gas cleaning systems. (iii) less volatile metals concentrate in bottom ash, which could require additional handling and disposal costs, in particular if ASR is classified as a hazardous waste. (iv) Finally, shredding plants usually do not process only cars, thus shredder residue pre-treatment can be expensive in order to meet input purity requirements of pyrolysis reactor.

However, since the latest generation of pyrolysis technologies are designed to accept a wide variety of resin types, can tolerate many forms of contamination and require little pretreatment before being fed into the system, *plastic to fuel* (PTF) technologies could present a potential alternative to landfill non-recycled plastics. The main problem related to pretreatment is that sorting technologies are extremely expensive and need dedicated expertise (see chapter "*Mechanical based ASR recycling technologies*"). So far, if the pre-treatment is loaded to PTF plant it could result both inefficient and too expensive. The cost per ton of the less expensive mechanical separation PST , VW – SiCon, is around 20-50 euro/ton (GHK/BioIS, 2006).

Currently, all the pyrolysis experiments reported in literature on ASR (Mancini et al., 1020; Donaj et al., 2010; De Marco et al., 2007; Zolezzi et al., 2004; Day et al., 1999; Nourreddine, 2007; Vermeulen et al., 2011) are aimed ad energy recovery and none of them reports chemicals production. Directive 2000/53/EC defines recycling as *''the reprocessing in a production process of the waste materials for the original purpose or for other purposes but excluding energy recovery, (while) energy recovery means the use of combustible waste as a means to generate energy through direct incineration with or without other waste but with recovery of the heat.''* So far, according to Directive 2000/53/EC definitions, if most of the liquid and gaseous products of these technologies are further used as fuels, the ELV energy recovery rate is boosted, while the recycling rate is unaffected (Santini et al., V).

In this chapter, a simulation of thermal PST is carried out. Further details are reported in Santini et al., V.

ASR pre-treatment

A sample of about 10 kg of light ASR obtained from a shredding plant in Rome, Ecofer s.r.l. (Gruppo Fiori), was used in this trial. On the sampling day, the shredding mill feed consisted of 34.93 tonnes of de-polluted car hulks. Car fluff samples were generated according to a standardized methodology (Italian standard UNI 10802:2004) by a quartering procedure starting from an initial cake of 360 kg.

Owing to the various particle size, sieving was applied. This resulted in two main fractions, fines (0–20 mm) and > 20 mm. In fact, fines may account for up to 50% of the total ASR mass (Morselli et al., 2010) and one of the goals was to understand if fines had a similar cracking behavior, compared to the raw material or the coarser fraction, which is directly related to organic content. Flotation and pyrolysis experiments were conducted on these two fractions plus an untreated one (U).

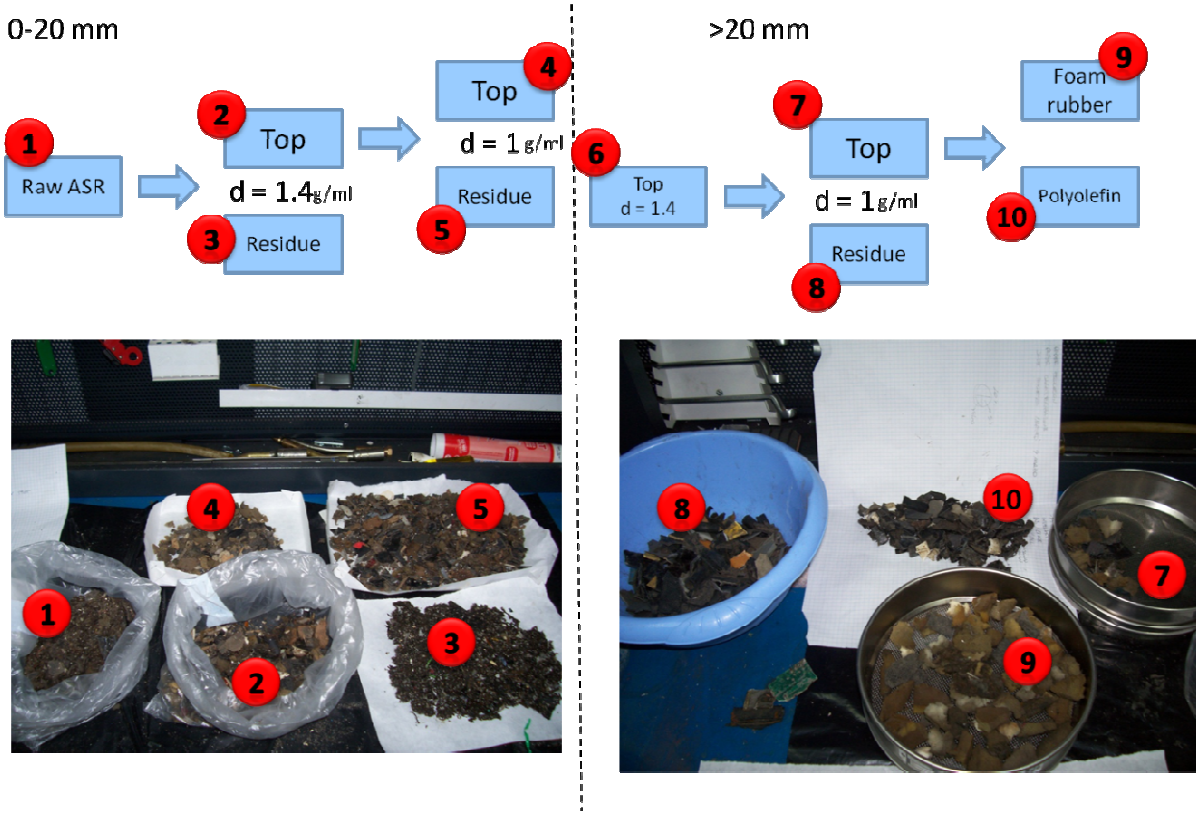


Figure 62 - Sample creation worksheet

Samples were floated in a 15-liter container. In order to separate the polymer fraction from the residue, a solution with density (q) equal to 1.4 kg/l was prepared. The solution was created by adding 660 g of potassium carbonate for each liter of water. The mixing temperature was around 75°C and the final density after cooling was 1.395 kg/l. Each sample was floated for about 15 min and then, with a sieve, the floating fraction was extracted, washed, and dried. Samples 6 and 2 were floated afterwards with distilled water as well, with density equal to 1 kg/l, in order to separate polyolefin (PE, PP) and foam rubber (PUF) from the heavier plastics mix. In sample 7, polyolefin and foam rubber have been manually separated for two further separated pyrolysis experiments (samples 9 and 10).

Figure 63 - Quartering and floating equipment

Figure 64 shows the materials sorting analysis of sample U obtained by gathering light and heavy fractions from the q = 1.4 kg/l flotation experiment and its material composition. This material distribution is very similar to the one the authors found in a previous work even though this ASR sample came from a different shredding plant (Morselli et al., 2010). Still, fines represent almost 50% of the total fluff, of which 19% are particles with diameters smaller than 2 mm. Polymers account for 33% in mass, of which 22% are ‘‘plastics’’ and 11% foam rubber. By using water floatation it is possible to identify polyolefin, which accounts for roughly 40% of the plastics total, confirming car manufacturers’ statements (Plastic Europe, 2010).

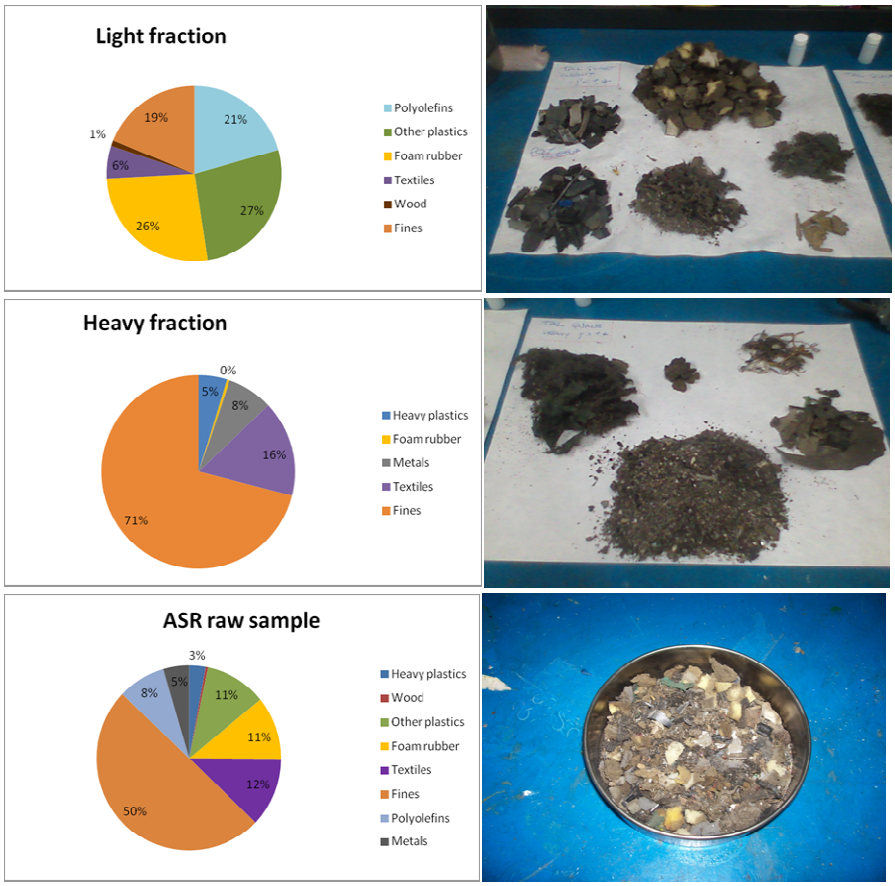


Figure 64 - Samples commodity analysis

Pyrolysis bench-scale reactor

In total, ten (1–10) samples plus an untreated (U) one were prepared (Figure 65 - Samples ready for pyrolysis). Each sample had a final 10 or 15 g mass, depending on its density, because the pyrolysis reactor had a capacity of 100 ml. Each sample was obtained by a quartering procedure starting from raw or floated material.

Figure 65 - Samples ready for pyrolysis

The experimental installation used in the present study for the ASR thermal cracking experiments is shown in Figure 66 – Bench-scale pyrolysis reactor.

Figure 66 – Bench-scale pyrolysis reactor

The equipment consists of a semi-continuous reactor provided with a helicoid stirrer. In a typical experiment, 10–15 g of the chosen sample were loaded into the reactor. After that, it was closed and the air in the reactor was removed by a continuous nitrogen flow (40 ml N/min) by properly setting the control panel.

Subsequently, the reactor was heated up to the reaction temperature, 500°C, which was maintained for 1 h. Reaction temperature and duration were chosen according to both TGA experiment results and literature overviews (Day et al., 1999; Harder and Forton, 2007; López et al., 2010).

While cracking products were forming, the nitrogen flow swept them into two coolers, the first one filled with water at room temperature for collecting waxes and heavy oils (H.oil), and the second filled with ice for collecting lighter substances (L.oil). The gases then passed through the air cleaning systems consisting of two scrubbers in line, filled with HCl and NaOH, respectively, before ending up in a Tedlar gas bag. Once cooled down, the reactor was opened and the solid residue removed. All the products and residues were finally weighed and the masses determined by the difference with the empty storage container. Oils, gas, and solid yields were calculated as percentages on the initial sample mass. Being a batch experiment, and due to reactor and trap shapes, it was not possible to recover all the reaction products, especially liquids and solids, during the reactor cleaning operations. Therefore, the mass balance varied between 80% and 95%, depending on the sample behavior. The total conversion was calculated as the sum of the liquid and gas yields. Moreover, catalytic cracking experiments were carried out by adding a nanocrystalline HZSM-5 zeolite catalyst (crystal size approximately 35 nm) together with polymer-rich samples directly in the reactor, creating samples 7C, 8C, and 10C, respectively.

Figure 67 – Pyrolysis oil collection

Mass balance

Sample	*Mass (g)*	*H.oil*	*%*	*L.oil*	*%*	*T.oils*	*%*	*Gas*	*%*	*Residue*	*%*	*Total*	*Loss*	*%*
1	15.0	2.6	17.3	0.1	0.7	2.7	18.0	1.3	8.3	9.7	64.7	13.7	1.4	9.0
2	10.0	4.8	48.0	0.4	4.0	5.2	52.0	0.9	9.4	2.2	22.0	8.3	1.7	16.6
3	15.0	0.0	0.0	0.4	2.7	0.2	1.3	1.0	6.5	11.6	77.3	13.0	2.0	13.5
4	10.0	5.3	53.0	0.5	5.0	5.8	58.0	1.0	10.0	0.9	9.0	7.7	2.3	23.0
5	15.0	7.3	48.7	0.0	0.0	7.3	48.7	1.0	6.8	5.4	36.0	13.7	1.3	8.5
6	10.0	3.9	39.0	0.5	5.0	4.4	44.0	1.8	17.7	3.3	33.0	9.5	0.5	5.3
7	10.0	5.4	54.0	0.4	4.0	5.8	58.0	1.1	11.3	0.9	9.0	7.8	2.2	21.7
8	15.0	6.8	45.3	0.0	0.0	6.8	45.3	1.2	8.2	4.8	32.0	12.8	2.2	14.5
9	10.0	4.7	47.0	0.2	2.0	4.9	49.0	1.0	9.6	2.5	25.0	8.4	1.6	16.4
10	15.0	11.8	78.7	0.7	4.7	12.5	83.3	1.1	7.4	0.7	4.7	14.3	0.7	4.6
U	15.0	1.7	11.3	0.4	2.7	2.1	14.0	0.8	5.2	9.2	61.3	12.1	2.9	19.5

Figure 68 - Mass balance

Figure 68 shows the product yields of the pyrolysis of ASR samples obtained by hydro-mechanical pre-treatment. Starting from the two raw samples, U and 1, it is possible to notice that they have a similar behavior in product distribution. Differences in yield per product are very small, considering the complexity and input variability of this waste.

Results are in line with literature for to raw ASR pyrolysis, taking into account reaction temperature, especially concerning the oil yield, which is the main goal of this work (De Marco et al., 2007; Zolezzi et al., 2004; Day et al., 1999). Total conversion is 19% for sample U and 26% for sample 1, which is rather low for any industrial plan, but this study is focused on treating plastic-rich fractions and comparing their performances with untreated samples.

Starting with the finer fraction, floatation effects can be seen between samples 2 and 3. By separating polymers from residues, oil yields almost triples in sample 2 if compared with the raw samples, rising from 14% to 52%. Oil conversion of bottom residues in sample 3 is only 2.7%, almost five times less than sample U. This result shows that floatation with d = 1.4 kg/l media is a suitable ASR pre-treatment for separating polymers for a further thermal (or mechanical) recovery. A second flotation with water, generating samples 4 and 5, shows that the top fraction, consisting mainly of polyolefins, wood, and foam rubber, still increases oils yield and reduces solid residue. However, with regard to recycling targets, sample 4 represents only 1% of the total raw ASR mass, while sample 2 represents 25% of the fine fraction, meaning roughly 12% of the total ASR mass.

With reference to the coarser fraction, sample 6 is supposed to have a similar material composition as sample 2, but different particle size; the same criteria may be applied to samples 4–7 and 5– 8. As highlighted in Figure 68, the matching up of the conversion rates of samples 2, 4 and 5 with those of samples 6, 7 and 8, respectively, reveals an extraordinarily similar cracking behavior: oil and gas yields are just a few percentage points apart in these two groups of samples. This is mainly due to the intrinsic product input dependency of pyrolysis, and underscores the importance of waste pretreatment in achieving high conversion rates (López et al., 2010; Harder and Forton, 2007). In addition, the polyolefins and foam rubber mix (samples 7 and 4) show better performances than the initial plastics mix (samples 2 and 6) and, when they are removed, the resulting heavy plastics mix (samples 5 and 8) have lower conversion performances. This effect may be ascribed to the presence of polyolefins in view of the fact that sample 10 shows a conversion higher than 90% (in line with Williams and Slaney, 2007), while the foam

rubber conversion in sample 9 has a cracking behavior comparable to samples 2 and 6. Moreover, polyolefins lead to very low solid residues, which results in waste management-related economic savings. Nevertheless, in samples 3 and U it was possible to easily sort metal pieces, springs, and copper wires from the car. Therefore, another pyrolysis application may be volume reduction and metal liberation for the recovery of heavy fluff fractions.

At room temperature polyolefin oil appeared as a straw-yellow liquid, while all other pyrolysis oils condensed in the coolers in this study were dark brown semi-solid, wax-like compounds at room temperature, especially sample 1 and U, which were almost black (López et al., 2010).

Figure 69 - Sample 1 pyrolysis oil

In sample 7, which consists of 25% foam rubber and 75% polyolefins in mass, the oil was reddish due to the abundance of polyurethane (PUR), as found in sample 9, which was definitely red-colored (Zia et al., 2007). A chromatographic qualitative assessment revealed that samples U and 1–9 pyrolysis oils were made of heavier products, particularly molecules with more than 14 carbon atoms, than sample 10. For this reason, the latter might be a good starting point for a further refining step to produce gasoline/ diesel fuels. As an alternative, aiming to raise the ELV material recycling rate in accordance with the Directive 2000/53/EC definition, sample 10 can be used in chemicals production, obtaining products such as olefins or aromatic hydrocarbons.

Gas composition

Sample	*Gas(g)*	*%*	*Methane*	*Propilene*	*Propaol*	*Buthene*	*1-Me buthene*	*C5*	*Tot*
1	1.5	10.0		24	6	15	29	17	91.0
2	1.1	11.3		18	3	17	19	12	69.0
3	1.2	7.8	19	30	6				55.0
4	1.2	12.1		37	4		26	12	79.0
5	1.2	8.2	10	45			18	6	79.0
6	2.1	21.4		33	9		26	8	76.0
7	1.4	13.6	6	37	9	4	12	5	73.0
8	1.5	9.9		30	3	10	36	6	85.0
9	0.7	14.7	[14%]	86					86.0
10	1.1	7.4		26	10	22	27		85.0
U	0.9	6.3	13	46	3		9	5	76.0

Figure 70 - Gas composition

Although in industrial applications C1–C5 hydrocarbons are currently used for generating heat (Harder and Forton, 2007), gaseous products could be also refined and exploited as chemicals in order to enhance the ELV recycling rate. Without catalyst addition, the obtained gas yields vary from 5% to 10%, and the relevant composition is shown in Table 2. In sample U, propylene is the most abundant gaseous product and is particularly abundant in foam rubber cracking (sample 9). Foam rubber represents 11% of the total ASR mass, but is a larger share of its volume. Foam rubber pyrolysis may be an interesting treatment at the industrial scale, considering both the waste volume reduction to 25% of solid residues and the gas conversion of roughly 10%, with almost 70% propylene which, in addition to energy recovery, is a high-quality chemical building block.

Pyrolysis oil composition

The main product in pyrolysis is cracking oil that can be used as fuel for power generation, or like building block in the chemical industry. The composition of the obtained oils have been analyzed by means of chromatography in order to obtain useful information, such as the number of carbons.

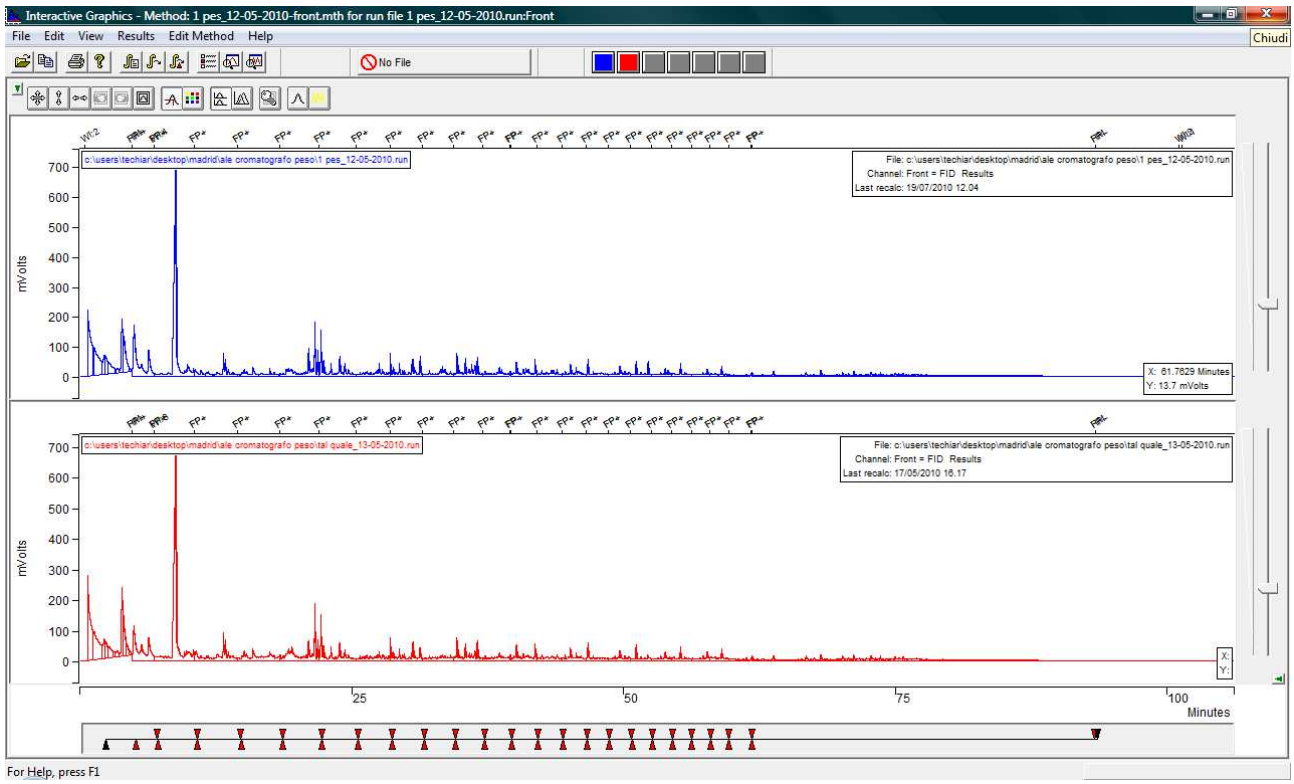


Figure 71 - Sample 1 and sample U chromatography

Figure 71 reports sample 1 and sample U chromatograms. Generally, light substances have shorter retention times and indicates a good cracking while heavier products, such as waxes, reveal longer retention times and usually are much more difficult to store and process. As it is possible to notice, sample 1 and sample U report similar chromatograms and late time peaks indicates the presence of very heavy substances .

Figure 72 reports chromatograms of sample 1 and sample 10. Of course, sample 10 reports more peaks at shorter times, indicating a lighter oil composition. This indicates that polyolefin produces a lighter oil, whit a high refining potential for fuel or chemical production.

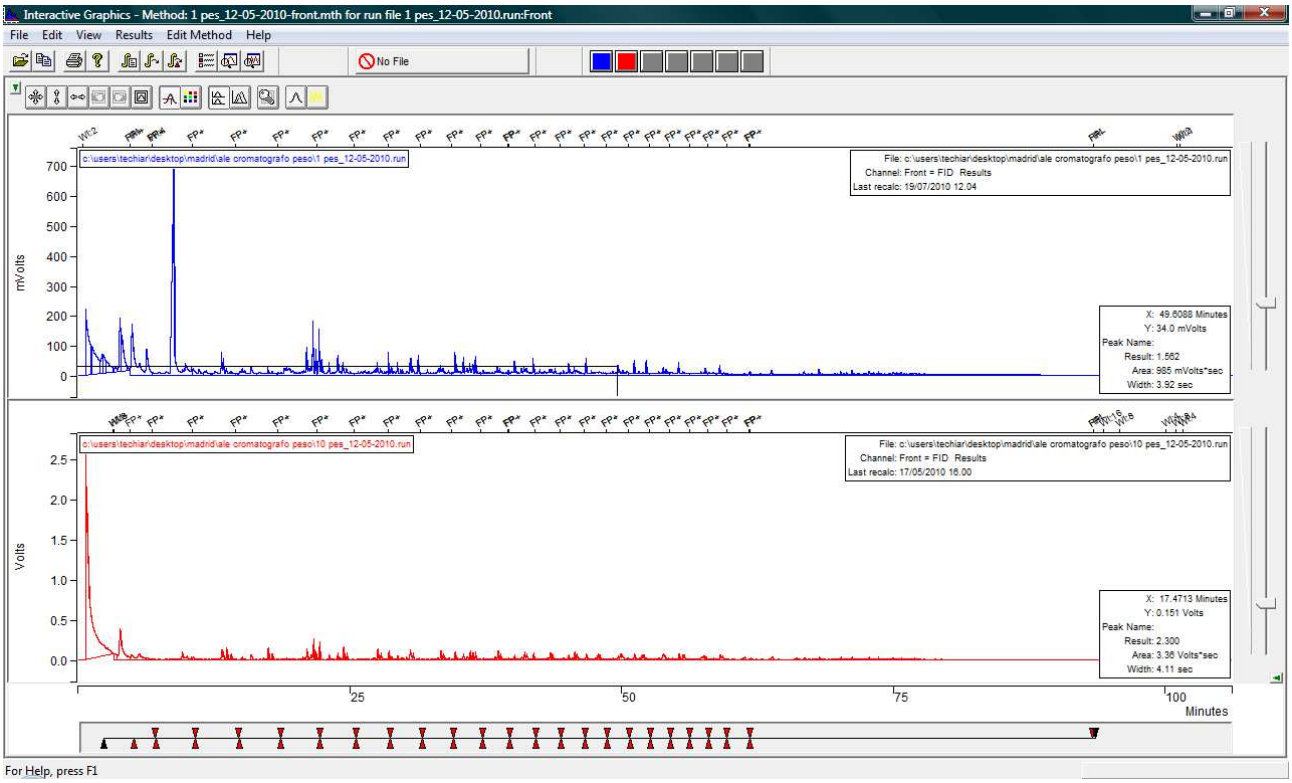
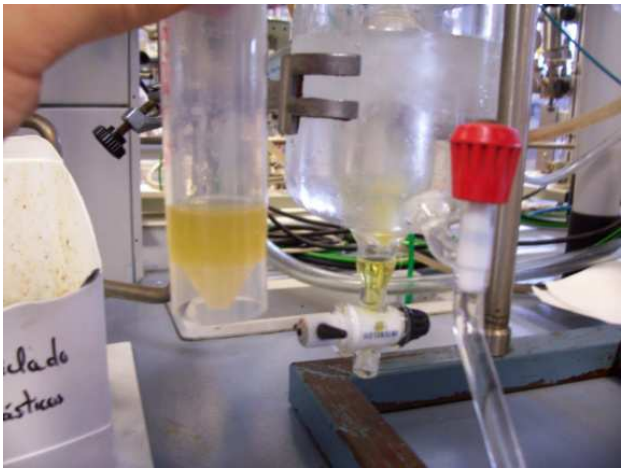


Figure 72 - Sample 1 and sample 10 chromatography



Hydrocarbon Totals by Group Type

Type	Wt %	Vol %	Mol %
Total Aromatics	4,997	4,141	4,699
Total C14+	16,187	15,471	9,817
Total Iso-Paraffins	8,374	8,972	10,611
Total Naphthenes	7,918	7,345	8,372
Total Olefins	16,652	16,972	18,261
Total Oxygenates	0,560	0,510	0,960
Total Paraffins	10,571	11,041	11,858
Total Unknowns	34,742	35,549	35,424
Total:	100,00	100,00	100,00

Figure 73 - Sample 10 oil picture and PIONA analysis

Catalysis experiments

In order to avoid an oil-refining step, some runs were conducted using a nanocrystalline HZSM-5 zeolite catalyst placed in the reactor together with the plastic-rich samples (namely samples 7C, 8C, and 10C). The aim was to produce a lighter, less viscous oil from plastic-rich samples. In samples 7C and 8C, the catalyst did not work, and this may be ascribed to coke formation and consequent active-site deactivation, while the catalytic conversion of polyolefins yielded a larger share of gas than the non-catalytic one, despite the fact that total conversion remained almost the same (see Fig. 4).

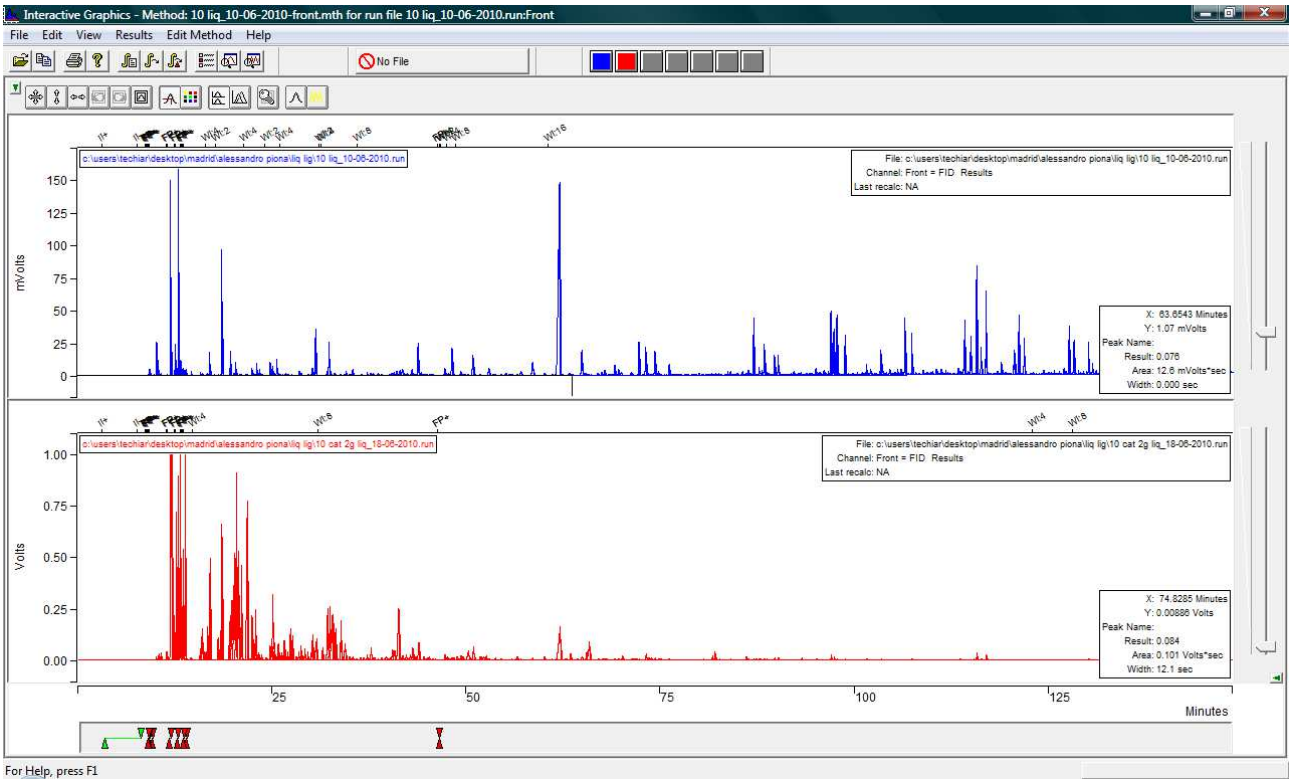


Figure 74 - sample 10 and sample 10C chromatography

As hoped for, the pyrolysis oil in sample 10C was less viscous and clearer than in sample 10 and the solid residue consisted of just the catalyst and some black powder. Moreover, this catalyst actually enhanced cracking by cutting hydrocarbons chains down shorter, and thus producing three times more gases than sample 10 as well as lighter compounds in the oil (as shown in Table 1). As was found in other pyrolysis studies (Serrano et al., 2003; López et al., 2010; Day et al., 1999; de Marco et al., 2007), these oils are rich in aromatics, olefins, paraffins, isoparaffins, and heavier hydrocarbons (more than C14). Table 1 shows the results of the PIONA (Paraffin, Isoparaffin, Olefins, Naphthenes, and Aromatics) analysis of samples 10 and 10C.

Hydrocarbon Totals by Group Type

Type	Wt %	Vol %	Mol %
Total Aromatics	4,567	3,597	3,761
Total C14+	1,163	1,039	0,477
Total Iso-Paraffins	11,422	11,189	9,245
Total Naphthenes	4,804	4,267	4,201
Total Olefins	40,898	40,839	42,510
Total Oxygenates	0,531	0,450	0,623
Total Paraffins	4,596	4,698	4,391
Total Unknowns	32,018	33,920	34,793
Total:	100,00	100,00	100,00

Figure 75 - Sample 10C oil picture and PIONA analysis

Some differences may be spotted: the catalyst reduces 10 times as many products with high molecular weight and increases unsaturated hydrocarbons. Obtaining products with less than 20 carbon atoms is very important for avoiding solidification of the oils during transport, storage, and use. In order to meet gasoline

or diesel requirements, both 10 and 10C oils must be further refined, and this expensive operation may hinder ASR pyrolysis in closing the loop in the automotive industry, from ASR plastic waste to gasoline fuel.

Sample	*Mass (g)*	*H.oil*	*%*	*L.oil*	*%*	*T.oils*	*%*	*Gas*	*%*	*Res*	*%*	*Total*	*loss*	*%*
10	15.0	11.8	78.7	0.7	4.7	12.5	**83.3**	1.1	**7.4**	0.7	**4.7**	14.3	0.7	**4.6**
10 cat	15.0	7.0	46.7	1.3	8.7	8.3	**55.3**	4.2	**27.7**	0.5	**3.3**	13.0	2.0	**13.6**

Figure 76 - sample 10 and sample 10C mass balance

Sample	*Gas(g)*	*%*	*Methane*	*Propilene*	*Propanol*	*Buthene*	*1-Me buthene*	*C5*	*Tot*
10	1.11	**7.4**		26	10	22	27		85
10 cat	4.16	**27.7**	13	46	3		9	5	76

Figure 77 - sample 10 and sample 10C gas composition

Conclusions

This work has been focused on ASR recycling by means of separation techniques followed by pyrolysis. The main goals were testing both pre-treatment techniques and pyrolysis in order to produce oils and gases suitable for further refining as chemical building blocks or gasoline.

Pre-treatment tests revealed floatation to be a good method to sort polymers from the multi-material matrix, while sieving revealed to be not the optimal solution. Polymers and light components amount to a 40% of the total raw mass, but they are only 25% of the fine fraction.

Pyrolysis of the Raw ARS sample revealed a close to 20% conversion while floated samples produces more than 50% oils and around 10% gases, thus reaching almost 60% total useful conversion. Fines (which accounts for a half of the total mass once sieved) present a cracking behaviour that is the same as the coarser and raw fractions, meaning that sieving is not the optimal pre-treatment solution if aimed at producing a pyrolysis feed. A further floatation with water, separating foam rubber and polyolefin, can increase pyrolysis yield in another 10%. Moreover, a sample consisting only of polyolefins reached 90% conversion while PUR sample had an interesting gas composition, with up to 70% propylene. The introduction of a ZSM-5 catalyst in the reactor is not worthy in samples with high solid residue because of the poisoning effect due to the char formation, while in polyolefins catalytic conversion almost triples gas yield and make liquid product lighter and more attractive towards gasoline production. Polyolefins revealed to be particularly suitable for chemical recycling applications, being a convenient material to use in cars when applying design for recycling criteria.

Finally, innovative recycling techniques and pyrolysis oil refining are key factors in reaching ELV Directive targets in 2015, since eco-design effects are not expected in the short run. Thus, improving yields, obtaining lighter products and reducing solid residues (and related disposal costs) are still open challenges in which catalysts can play a key role in a “waste to chemicals” approach. This study has revealed that reaching ELV directive recycling target is theoretically feasible but further studies must be performed in this direction. A great innovation is expected in the forthcoming years due to the 85% recycling rate threshold approaching, with chemical recycling being a strong candidate to research on.

Thermodynamic Cracking technology plant

In the framework of the research on thermal based technologies, a study performed by the University of Bologna and Cracking Energy Machines Ltd. was aimed at optimizing a Thermodynamic Cracking process. The research involved the analysis of the chemical and physical properties of shredded or pelletized end-of-life tyre rubber feedstock intended for processing in the thermodynamic cracking.

Particular attention was given to chemical and physical properties of the end products (currently envisaged to be diesel fuel, liquid petroleum gas and carbon black) produced by the thermodynamic cracking process. Aims of this work were the understanding of the cracking system itself under mechanical and chemical-physical points of view. Products characterization and recommendations for improvements to enhance the reliability, functionality and efficiency of the thermodynamic cracking process itself were additional targets accomplished during the cooperation.

This process, developed by Mr. Giorgio Pecci (CEML Ltd.), falls into the "plastics to fuel" technologies, PTF (*cf* 4R, 2011). In general, PTF systems produce three outputs: natural gas, the liquid fuel product and char. The gaseous hydrocarbons can be rerouted into the system to account for a part of the system's energy needs, or it can be flared by means of a torch. The majority of the systems do capture the energy from this gas, however this will vary case by case. In terms of main fuel product, the output of these systems can be quite different. Some of the systems under development produce a gasoline-diesel fuel blend that needs further refining. Some generate a product similar to sweet crude oil that needs to be refined, but it can become a variety of products and other PTF systems produce diesel fuel ready for use in vehicles or in power generators. Most of the technology manufacturers that have pilot-scale facilities in place, and offering systems that have fuel outputs which require further refining or blending by a third party have had their products tested and processed to ensure that the output is indeed a usable product that would have a market (4R, 2011).

Char is the solid residue material remaining once the pyrolytic process is complete and the fuel and gases recovered. Char contains the additives and contaminants entering the system as part of the feedstock. The char can be a powdery residue or substance that is more like sludge with a heavy oil component. Glass, metal, calcium carbonate, clay and carbon black are just a few of the contaminants and additives that will remain after the conversion process is complete and that become part of the char. In many cases, technology manufacturers said the char was a benign material that could be landfilled. In some cases, technology manufacturers are exploring applications for the char. Some of those exploratory applications include road, active carbon, carpet and roofing material. PTF technology manufacturers often suggest additional energy recovery as the best management option for the char. Since there is a carbon component in the char, this material can be sent to an incinerator, into a coal-fired power plant, or burned on site for additional energy recovery. These alternative uses for the char make the conversion process potentially a zero-landfill management option for non-recycled scrap plastics (4R, 2011).

Common features of these systems include:

1. **Pretreatment** –this could be performed according to the size reduction or much intense as specific materials or maisture removal.
2. **Conversion** – pyrolysis is used to convert the plastic to a gas.
3. **Distillation** – the gas is cooled to liquid form. At this step, by some kind of cheap fractional distillatory, the hydrocarbon mixture could be further separated in gasoline-like and diesel-like compound.

4. **Acid removal process** – removal of acids that form in the breakdown of some scrap plastics (mainly PVC or sulphur contained in vulcanized rubber). These acids require removal because they can be corrosive to the PTF systems as well as the engines that will consume the fuel.
5. **Separation/refining/final blending** - the final steps required to make this product consumer ready can either be done on site or by a third party, depending on the system design (4R, 2011).

Figure 78 reports the process flow diagram of Cynar Plc, an Irish company which developed a pyrolysis technology for treating mixed plastics waste.

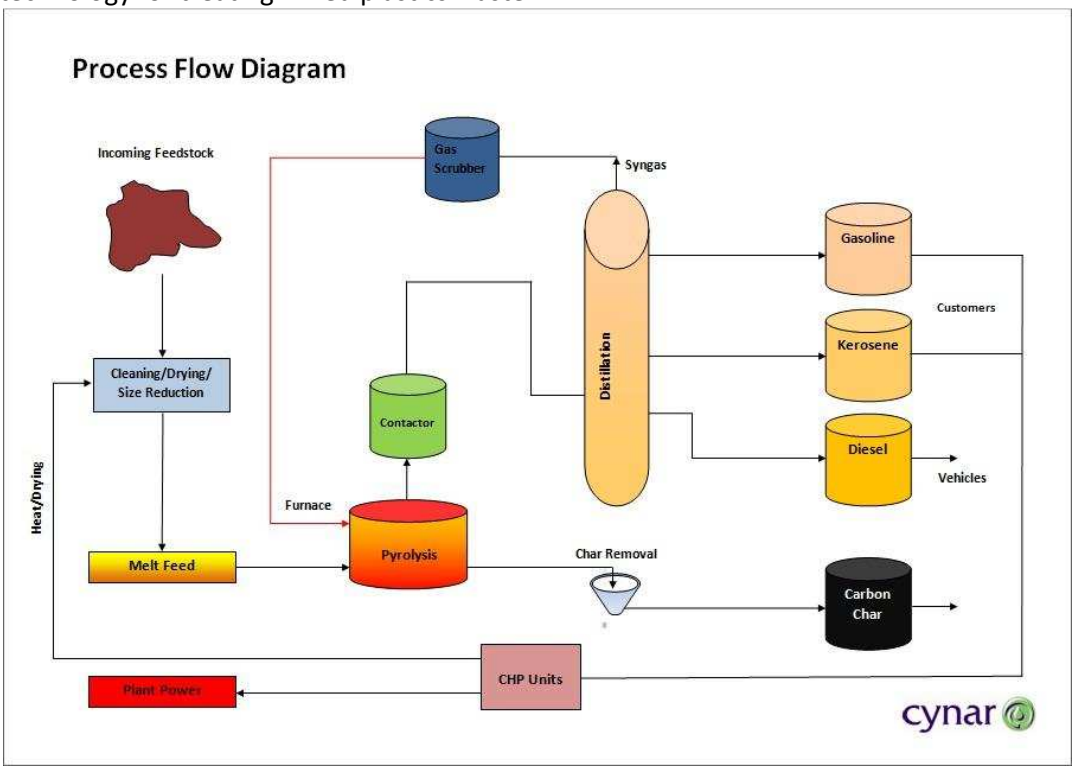


Figure 78 – Cynar Technology - Process Flow Diagram (source: http://www.cynarplc.com/cynar_technology.asp)

According to the 4R PFT report, the majority of these companies have pilot-scale facilities which tend to be about one-fifth/one-half of the size of the smallest recommended capacity for a commercial-scale facility. The others listed have "bench scale" systems which are even smaller demonstration systems. The development of pilot-scale facilities has generally taken most firms three to five years and, of course, the financial resources that have been made available to developing the technology will also have an impact on the size of the facility. Return on investment (ROI) is generally quoted at two to five years, if all cost conditions and product pricing hold steady (4R, 2011). Factors that could impact the length of ROI include changes in energy costs, price of oil and fuel, and cost and availability of scrap plastic (4R, 2011).

During the third PhD year, the study of one among the few industrial-scale PTF technology has been carried out (Thermodynamic Cracking reactor by CEML). Particular attention was given to the analysis and identification of uses to which end products may be addressed. Moreover, a comparison of the performance characteristics of the thermodynamic cracking process is reported, in relation to incineration and pyrolysis processes. Energy balance of the system itself is calculated, with the energy output of the end products of the thermodynamic cracking process compared to other processes designed to generate electricity from tyres.

Plant description

The thermodynamic cracking plant studied has been designed to process rubber coming from end of life tyres (ELTs), on the basis of industrial patents BO2006A603 and BO2006A613. The whole system has a capacity up to 700kg/h and it can be fed with polymeric materials ranging from 2 to 20 mm. The goal of this technology is to convert a solid waste into a liquid fuel through the cracking of high molecular weight polymers into liquid and gaseous hydrocarbons with lower molecular weight. The most important outputs of this process are:

- a gas rich in hydrocarbons with maximum six carbon atoms,
- a liquid cracking oil,
- and a solid powdery residue.

The liquid and gaseous products obtained from this process can be used for power generation, but also for different further processes, like catalytic refining aimed at chemicals recovery. As shown in Figure 79, the Thermodynamic Cracking plant is very compact and no direct emissions to the air are produced during the feed material conversion.

Figure 79 - Thermodynamic Cracking plant overview

System operation

The material is firstly loaded up into a hopper and subsequently sucked into two feed tanks. Such procedure enables both the transport and monitoring of materials that may not be complying with the requirements or be potentially dangerous for the reactor, e.g. spring steel contained in tyres. By means of a auger at an adjustable speed, the rubber is sent to the reactor in which thermal decomposition takes place.

The reactor is composed of two longitudinal rotors, supported in the upper part in order to ensure mechanical strength. In their first part, the axes of rotors have an helical profile to feed, heat and speed up the material towards the decomposition chamber. A thermal insulated cover separates the rotors from outside. Such cover is heated with a temperature gradient ranging from 350°C -at the output of the auger- to 400°C -in the decomposition chamber -. The tolerance of the cover is extremely precise and therefore it correctly adjusts the fiction of the material against walls and rotors. The profile of the axes of rotors changes in the decomposition chamber , thus favouring the friction of the material, now viscous, with moving mechanical parts. The difference with a traditional pyrolysis process is that this system allows the cracking of the material at lower temperatures and a higher heat transmission. Friction turns kinetic energy into thermal energy which spreads in the material by means of direct conduction instead of irradiation from outside the reactor. Hence, it allows a considerably rapid heading (flash) which favours the production of unsaturated liquid molecules at room temperature, namely the cracking oil.

Once the transformation process is terminated, products move through a distiller provided with two self-cleaning twin augers which remove carbon, allowing gas to go into two condensers located one after the other. The liquid products that are collected in the condensers and the gases are stocked in special tanks, ready to be used for the production of electric energy. The carbon is cooled down with water jets and dried up on a rotating drum. The vapour produced during this passage is conveyed in a washing tower and the water is reused in a closed circuit.

Working parameters

In Figure 80 the plant operating scheme is reported, completed by standard working parameters. Temperatures are reported both as set by the user (Ti) and as recorded (Tr).

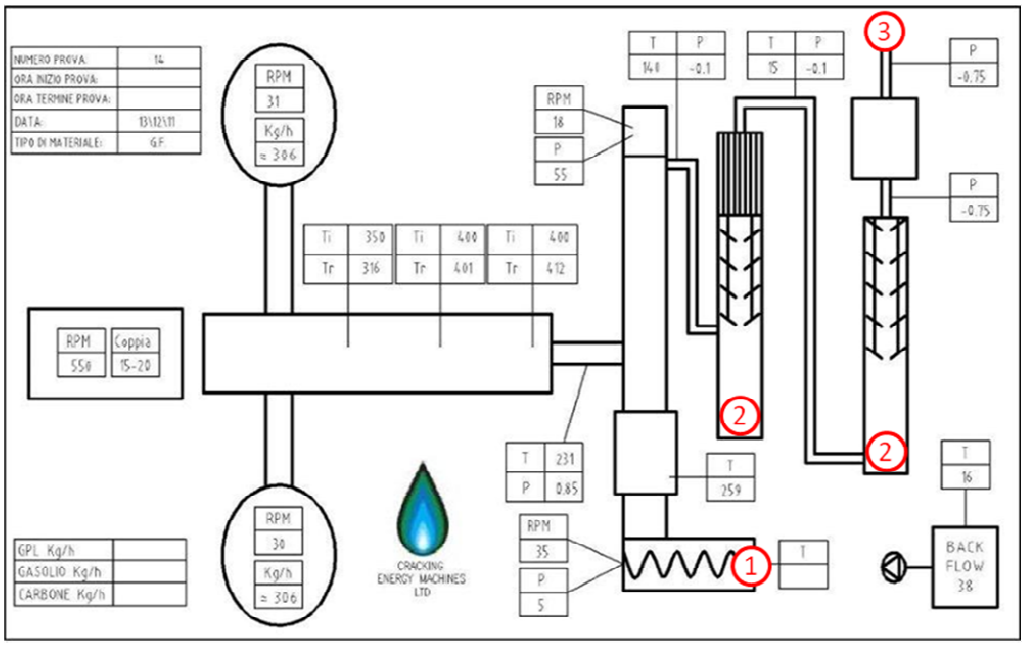


Figure 80 -Thermodynamic Cracking plant worksheet

In this worksheet, from left to right, the first box represents the main motor and RPM indicates the speed of the main motor powering the reactor shaft. The black circles indicates the two feed hoppers and the material flow rate. The three temperatures in the reactor indicates respectively the temperature at which the input material enters into the reactor heater, the temperature at which the cracking begins in the cracking chamber and finally the temperature at which the reaction ends. Other parameters represents temperatures (T) and pressures (P) registered at distillers, coolers and carbon collecting systems. In the distiller and in the carbon drying drum, RPM indicates the carbon cleaning and recovery auger operational speed.

Sampling scheme

During the sampling day, the reactor and the distiller have been heated up to the working temperature. Due to the limits stated by authorizations and to feed availability, it was not possible to run long term tests (more than 24h). The starting phase is very critical for this kind of system because reactor and distiller temperature are critical parameters for both cracking itself and recovered product quality.

Feeding rate has been fixed at around 750 kg/h, and samples of char, oil and gas have been collected once the system reached the stationary state from red collection points 1,2 and 3 respectively in Figure 80. The samples have been kept in adequate vessels and analyzed by a certified, independent lab (Intertek Caleb Brett s.r.l.). Chemical analyses were performed using international standard method. All the parameters chosen to characterize the products were arranged in order to have a clear view of the process.

Mass balance

At the stationary state, solid and liquid samples have been recollected during one operating hour. Gas mass was calculated by difference. Results are reported in the following table:

Product	*% (by weight)*
Oil	50-55
Gas	20-30
Carbon	20-25

Conversion rate is about 80%, and it is in line with other plastic to fuel (PTF) technologies results. In terms of yield, the share of products indicates that Thermodynamic Cracking is very efficient in breaking down polymeric chains because the gaseous fraction is very high compared to a pyrolysis process operating at the same temperature. This result is even more satisfying when considering that no catalyst neither inert gas (such as Nitrogen) are used in this process . The main difference between this technology and other PTF is the oil and gas production rate. Usually, at 400°C, tyres oil production rate is lower in standard pyrolysis processes and char share is higher, meaning that cracking is not completed. With this technology it is possible to obtain roughly 50% oil ready to be used into a power generator. This is mainly due to the kinetic energy that this technology transmits to the softened rubber that, in addition to the external heat, enables cracking to happen at lower temperature. Differences in products share can rise from the peculiar mechanical stress, which is the basis of this technology, applied to the rubber material (see Section 2.1), which is a thermosetting material. In fact, with respect to standard pyrolysis systems, gas yield is more than two times higher with Thermodynamic Cracking. Being the main goal of this system power generation, a higher share of gas can be attractive due to its power conversion efficiency.

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Date accepted:	30 May 2011	*Sample container:*	Bottle	*Temp. °C:*	AMB
Grade:	LIQUID				
Delivered by:	C.E.M.L.				
Remarks:	SAMPLE NO. 2				

Sample Label

Location:	GORDONA (SO)	Date:	30/05/2011
Taken from:	CLIENT	Sampling mode:	N/A
Grade:	LIQUID	Seal number:	NOT SEALED
Society:	C.E.M.L.	Lot:	

Parameter	*Method*	*Unit*	*Result*
Water content	EN ISO 12937	mg/kg	870
Ash content	EN 6245	% wt	0,002
Asphaltens content	IP 143-04	% wt	0,30
Bromine content	UNI 15309	mg/kg	< 50
Chlorine content	UNI 15309	mg/kg	< 50
Total contamination	EN 12662	mg/kg	145
Copper strip corrosion (3hrs at 50°C)	EN ISO 2160		1a
Density at 15°C	UNI EN ISO 3675	kg/l	0,8906
Flash point	UNI EN ISO 2719	°C	< 21
Cetane index (calculated)	EN ISO 4264		35,2
Iodine content	UNI 15309	mg/kg	< 50
Pcb & Pct content	EN 12766	mg/kg	< 1 / < 1
Gross calorific value	ASTM D240-07	Kcal/kg	10412
Distillation atm			
- I.B.P.	EN ISO 3405	°C	97,8
- 5%	EN ISO 3405	°C	142,2
- 10%	EN ISO 3405	°C	160,9
- 20%	EN ISO 3405	°C	176,1
- 30%	EN ISO 3405	°C	209,2
- 40%	EN ISO 3405	°C	237,2
- 50%	EN ISO 3405	°C	265,1
- 60%	EN ISO 3405	°C	295,6
- 70%	EN ISO 3405	°C	326,1
- 80%	EN ISO 3405	°C	352,2
- 90%	EN ISO 3405	°C	382,8
- 95%	EN ISO 3405	°C	406,1
- F.B.P.	EN ISO 3405	°C	413,4
- recovered at 250°C	EN ISO 3405	% v/v	45,2
- recovered at 350°C	EN ISO 3405	% v/v	78,4
- recovered at 370°C	EN ISO 3405	% v/v	87,6
Sulphur content	ASTM D1552-08	% wt	1,60

*continued Analytical Report no. **11LA00255***

Parameter	Method	Unit	Result
Viscosity at 40°C	ISO 3104	mm^2/sec	2,589
Pour point	ASTM D97-08	°C	< -60
Micro Carbon Residue	ISO 10370	% wt	0,13
Metals			
- Aluminum (Al)	ASTM D7691	mg/kg	0,2
- Barium (Ba)	ASTM D7691	mg/kg	< 0,1
- Boron (B)	ASTM D7691	mg/kg	2,2
- Calcium (Ca)	ASTM D7691	mg/kg	< 0,1
- Chromium (Cr)	ASTM D7691	mg/kg	0,1
- Copper (Cu)	ASTM D7691	mg/kg	0,1
- Iron (Fe)	ASTM D7691	mg/kg	3,8
- Lead (Pb)	ASTM D7691	mg/kg	< 0,1
- Magnesium (Mg)	ASTM D7691	mg/kg	< 0,1
- Manganese (Mn)	ASTM D7691	mg/kg	0,1
- Molybdenum (Mo)	ASTM D7691	mg/kg	< 0,1
- Nickel (Ni)	ASTM D7691	mg/kg	< 0,1
- Phosphorus (P)	ASTM D7691	mg/kg	0,5
- Potassium (K)	ASTM D7691	mg/kg	< 0,1
- Sodium (Na)	ASTM D7691	mg/kg	26,4
- Silicon (Si)	ASTM D7691	mg/kg	26,2
- Vanadium (V)	ASTM D7691	mg/kg	< 0,1
- Zinc (Zn)	ASTM D7691	mg/kg	1,8

Concerning oil production, there is an inverse correlation between capacity and oil density and thus viscosity and distillation curve. When the feed flow is too high, the cracking is not complete, thus the oil is heavier. GHV, instead, is almost constant when varying the feed rate.

Critical parameters for oil classification and combustion are: gross heat value, distillation curve and sulphur content. GCV (10,412 kcal/kg equal to 43.8 MJ/kg) is in line with other liquid hydrocarbon fuels, like diesel, and it is suitable for power generation in diesel engines. The distillation curve reveals the liquid to be quite light and together with sulphur content lower than 1% and low viscosity, allow this product to be classified as “fluidissimo BTZ” according to Italian UNI 6579:2009. The flash point of the oil (>21°C) is well below the 55°C and 65°C limits set for diesel fuel and light fuel oil, respectively. Such a low value is not surprising since the product corresponds to an unrefined oil made of a mixture of components with a wide distillation range. Finally, the density (0.89 kg/m^3) and the kinematic viscosity of the oil at 40°C (usually below 3 mm^2/s), are similar to those of diesel fuel. Metal content is very low and metals present in the liquid usually can be ascribed to impurities of the feed material such as soil (for aluminium, boron and silicon) and iron powder resulting from steel separation process.

Gas composition reveals almost 70% hydrocarbon content, with a high methane concentration. Other C2 like ethane and ethylene are present in good concentration along with hydrogen. Carbon monoxide and carbon dioxide content is very high for such a cracking process occurring under an inert atmosphere. It is possible that the oxygen comes both from humidity and air adsorbed in the feeding material rough surface. Moreover, also nitrogen concentration itself is quite high, confirming that air is entering into the system. Gas GCV is high and in line with natural gas one conventionally used in power generation. Also sulphuric acid presence reveals water content, thus input material pre-treatment reveals a key factor for this technology, as well as for all other PTF, and a drying system exploiting the heat generated during product

oxidation shall be considered. Avoiding water and air to enter in the reaction chamber can lead to less carbon production and, moreover, to reduce ash and carbon content in the oil.

Char analysis reports an interesting GCV, 29.4 MJ/kg, a value in between coal and petroleum coke. Tyre-derived char may also participate successfully in co-combustion processes in pulverized coal power plants. However, the high sulphur content may hinder energy recovery route by direct incineration while carbon black substitution could be considered. Further test shall be performed in order to evaluate carbon black substitution.

Energy balance

The Energy balance is calculated as net power production, by summing up liquid and gaseous product contributions based on each specific heat value, minus the internal electric consumptions. Solid carbon combustion is not considered in this energy balance, even though it could follow energy recovery route as coke or coal. Internal electric consumption is the sum of main drive motor, hoppers, pumps, heaters, compressors and all other utilities, and it amounts at 98 kWh. During the trial, the gaseous fraction was flared as shown in Figure 81.

Figure 81 - Gas flaring torch

The oil was collected in a storage tank, as shown in Figure 82, and then used in a power generator.

Figure 82 - Diesel power generator

Finally, with an input of 611 kg/h of crumb rubber, the system can produce 5389 MW*h of thermal energy which could be converted into electrical energy. More in detail, a note of the power generation builder (http://www.cat.com low BSFC 400kW*h model) indicates that for each liter of oil feeding conventional reciprocating engines it is possible to produce about 4.83kWh. This means that during one hour operation, if the produced liquid fuel is completely used for generation, it is possible to obtain 360 l x 3.86 kW*h/l = 1.39 MW*h of electric energy, assuming a power factor of 0.8.
During the trial, cracking liquid fraction was blended with 40% commercial diesel to improve combustion properties. Tests with lower blending ratios are under development as well as exhausts gas sampling.

Conclusions

The cooperation between University of Bologna and CEML established a testing protocol useful to give reliability and order to the experimental data collected during plant operation. In this perspective, preliminary data obtained before the beginning of this research were collected and studied to give indications for new experimental design and procedures.

Results of this trial showed that it is possible to obtain about 50% cracking oil ready to be burnt into a power diesel generator. Another product obtained during the test has been a gaseous fraction accounting for about 30%, suitable for energy recovery, similarly to the natural gas. Moreover, the process produced a solid carbon powder which could be used as carbon black or for energy recovery.

With this plant, by burning the oil in power generator, it is possible to obtain about 1.39 MW*h of net electric energy output for each hour of operation.

Some aspects concerning product optimization arose during trails and data elaboration:

- Feed material should be dry enough to avoid air and moisture taking part at the process. In order to reduce oil and gases contamination, particularly due to water interactions with sulphur and rubber bringing to H_2S and carbon formation respectively, residue heat from gas and oil energy recovery equipment could be exploited.
- It is necessary to operate the machinery for a longer time in duration stress tests.
- A close examination of carbon powder resulting from this process and its possible application as carbon black could be fruitfully investigated.
- A life cycle assessment (LCA), comparing environmental performances of this technology with other tyres recovery process could provide interesting information, in view of a sustainability analysis.

The complex nature of tyres makes it difficult to recycle them. On the one hand the main component of tyres, rubber, is a chemically cross-linked polymer and, therefore, is neither fusible nor soluble and, consequently, cannot be remoulded into other shapes without serious degradation. On the other hand, tyres are a complex mixture of very different materials, which include several rubbers, carbon blacks, steel cord and other organic and inorganic minor components.

Currently, there is much interest in using these materials for energy generation. Tyre-derived fuels (TDFs) are used as substitutes of fossil fuels in the concrete industry and in combustion processes for the generation of electric power, e.g boilers in the paper manufacturing industry, by industrial boilers and by power stations, etc.

The main difference between Thermodynamic Cracking Technology and other pyrolysis treatments are the working temperature and the emissions of the system. With this technology operating at 400°C, oil yield is very high. Generally, such a share of liquid product is obtained at more than 500°C by pyrolysis. This means that kinetic energy is successfully converted into heat and participates to carbon bond cracking. Moreover, the liquid oil recovered with this technology can be easily stocked and, being suitable for internal combustion power generators, it can be used both continuously or on demand without expensive air cleaning system, if combustion is operated correctly by the engine.

Outlooks

- Gaseous products could be further refined, via separation membranes for instance, with the purpose of obtain chemical building blocks such as methane, propylene and /or buthanes.
- Liquid products may not just follow energy recovery route and they could be addressed to a petroleum refinery aiming at more valuable chemical production. Further analysis shall be carried out in order to have more details concerning oil composition.
- The solid product could be used as a carbon black back in the tyre industry. Trials shall be performed aiming at this specific employ.
- With a 1 ton/h plant, it could be possible to obtain 1.39MW*h x 1000/611 kg/h = 2.275 MW*h/ton by exploiting only the cracking oil.
- Tests shall be run with pre-treated heavy ASR as feeding material.

DISCUSSION AND CONCLUSIONS

There is a growing consciousness that waste is a design problem.

European Community addressed producer extended responsibility onto car producers since they are the only one accessing the design of products. Recyclers cannot reach the head of design and moreover they are never invited at the table to discuss about “good materials”, dismantling effort and recycling processes, especially now when the lightweight and electric vehicles revolution is at the doors. In short, since you cannot control all that leaks, control what enters the system.

Back to the aims of this PhD thesis, applying industrial ecology in ELVs management do not only means to improve ASR recycling processes, saving resources and avoiding environmental impacts. This approach shall be applied to the very first step of the product lifecycle: the design. At this step it is possible to determine the 80% of the environmental impact of a product, simply by considering recycling-relevant parameters into conceptual design. Each new material have effects on recycling and new markets for its recycled counterpart shall be established. Moreover, we are merged in a global economy and even though pre-shredding operations could definitely be the key in reaching recycling targets, if dismantle is difficult, destructive and not profitable, components are left in the hulk, shredded and they end up as ASR. Reusable components have high value held in low volume, while recyclable materials have low values, thus the latter need large volumes to be profitable.

ELVs shredding is a well established process and the challenge now is to recycle ASR efficiently and with environmentally sustainable technologies. ASR contains about 5% metals, 40% polymers, 5% glass, and the residual part is made of fines and other materials, such as paintings, textiles, paper and wood.

LCA, in line with to Directive 98/2008/EC on waste, revealed that among the currently existing scenarios, landiflling is a waste of resources and thermal recovery of ASR shall be preferred in a life cycle perspective. Landfill mining is an interesting perspective that is going to take place in the next future. Naturally, according to Directive 2000/53/EC on ELVs, PSTs are preferable and the best solution is an intensive material separation and recycle followed by thermal recovery of the non-recyclable -but high gross heat value- residue. Fines shall be sorted out before thermal recovery and they could be used as ASR landfill cover, in road construction or disposed in landfill if their share on the total ELV recycling rate is below 5%.

Aiming at complete metal separation, innovative sorting technologies have been studied and results indicate that, following the correct logic of process, metals can be removed from ASR in a efficient and profitable way. Metal separation from light fluff is operative at the Italmetalli shredding plant with a dedicated pilot line and its results are encouraging: currently 50 kg per hour of aluminum are sorted and recycled.

Figure 83 - Aluminum obtained by light ASR pilot line (January 2012)

This results triggered the investigation of complete metal recovery from light fluff, a task that is emergent in Europe and in which the candidate and the Gruppo Fiori wants to be pioneer.

Concerning heavy fluff treatment, copper wires and stainless steel were the most challenging metals to sort out. A dedicated 15 ton/h plant is under design and development and industrial trails indicates that complete metal recovery is possible also from this waste under a technologically proven, environmentally safe and economically sustainable conditions.

This brings to a polymer-rich fraction that with little pre-treatment can undergo enhanced plastic sorting and recycling or thermal treatments such as incineration, pyrolysis, gasification or a combination of the latter two processes. Thermal recovery of *car fluff* strongly depends on intensive preparation. ASR could be addressed to *plastic to fuel* technologies such as pyrolysis with encouraging results if pre-treatment is correctly carried out. 60% conversion can be achieved with bench-scale pyrolysis reactor. Moreover, polyolefin alone can reach 90% conversion. This result confirm that PTF technologies are input-dependant and that if less polymeric families are used in car design, the sorting efficiency is higher as well as the achievable recycling rate.

Thermodynamic cracking revealed to be a suitable technology for rubber crumb energy recovery. With about 2MW of power generated per ton of waste treated it resulted very energy efficient. In addition, trials will be performed on heavy ASR since after a complete metal recovery, almost 80% of its components are suitable for this technology. Pyrolysis liquid products could be used as such for energy recovery or further refined as chemicals. Great innovation is expected in this field within the next years to reach 90% recycling rate in 2015.

Finally, nowadays almost 50% of the de-registered ELVs are exported to other countries in which consequent disposal is not as safe and controlled as in Italy. This effect is worsened by the financial crisis which tempt dealers and dismantlers to trade with countries in which them are paid not just as wreck but as second hand vehicles. This issue can be reduced by placing law limits to the age of exportable cars and would be regulated by checking more carefully harbors and national borders. If this condition is going to last, shredders will struggle for buying hulks to process. This reduces the margins and the related capital which can be addressed to the investments that are necessary to improve recycling efficiency and reach ELVs Directive's targets.

Moreover, under a life cycle point of view, exporting ELVs is doubly negative: first, it represents a resources leakage and, second, along with scraps, the mining and metal refining embedded energy flows out.

Considering that it takes almost 2 years to design and build up a PST plant, and three to five years for a plastic conversion technology one, 2012 is going to be crucial for shredders business plan.

Recommendations

If waste are our new resources, landfills turn out to be our new mines. Waste management is going to be crucial in the forthcoming years to secure materials, especially minerals, supply.

Europe is going to be a low carbon and a recycling society but if the control of CO_2 emissions is the visible tip of the iceberg, to ensure resources and oil supply are the real aims of waste European policies. In general, Europe exports products but imports a lot of raw materials because it is a continent poor in mine resources. The automotive sector is one among the most resource-consuming sectors of the industrial compartment, and ELVs Directive targets are one among the Commission's tools to stop resource leakage

from Europe to developing countries. In fact, China and other fast growing Countries (Brazil, Russia, India China and South Africa, BRICS) are currently buying a wide share of the metal scraps produced by the world car recycling industry. This is a net impoverishment for Europe and a precious heritage for the other Countries, since the conversion of scrap to steel and other metals into ready-to-use resources allow savings up to a ten factor of the energy necessary to strip mine earth and extract resources in its primary sector of the economy. In practice, along with scraps, all the energy embodied in metals mining and production are delivered, one of the most environmental-concerning and resource-consuming activity. In this way, developing countries can reduce their huge resource hunger, but following waste management is not as developed as in Europe causing huge pollution and environmental crisis.

Future research

This 3 years passed quickly and some aspects of this PhD thesis demand further investigation:

1) the modeling of the optimal ELVs treatment chain, in terms of best practices and best available techniques for both the improvement of the ELVs recycling rate and the production of cleaner streams of secondary raw materials;
2) particular care will be given to light fluff metal recovery pilot line, especially aimed at copper wires, stainless steel and fine metals recovery;
3) a thermal recovery technology for light fluff is under test and development;
4) thermodynamic cracking technology applied to heavy fluff rubbers is under study and test;

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APPENDIX

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